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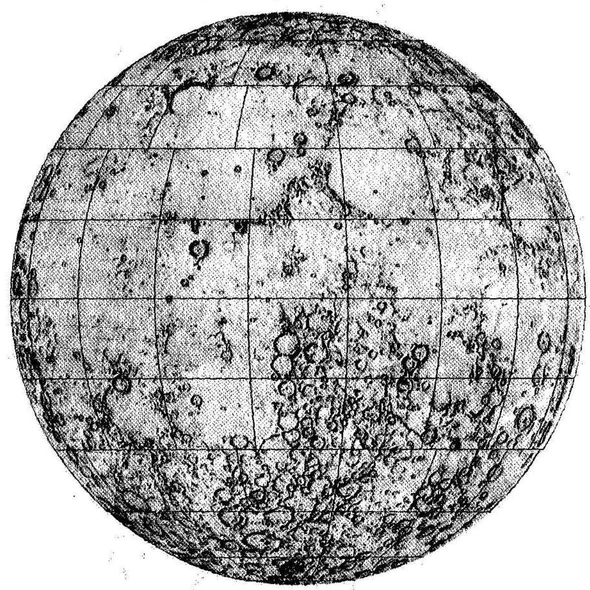
ANNUAL PROGRESS REPORT

October 1, 1967 to October 1, 1968



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October 1, 1967 to
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April 1969

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INTRODUCTION

This Annual Report is the ninth of a series describing the results of research by the U.S. Geological Survey on behalf of the National Aeronautics and Space Administration under contracts R-66; W-12,650; W-12,388; T-66353G; T-75412; R-09-020-041; WO-5171; and WO-3027 (in part). The report was prepared by the Branch of Astrogeologic Studies and others who have done work for this branch. This one volume summarizes results of research carried out between October 1, 1967 and October 1, 1968.

Long-range objectives of the astrogeologic studies program are to determine and map the stratigraphy and structure of the crust of the Moon and other planets, to determine the sequence of events that led to the present condition of the surfaces of the planets, and to describe how these events took place. Work currently leading toward these objectives includes: (1) A program of lunar geologic mapping from both telescopic and spacecraft photographs supported by photometric studies; (2) field studies of natural structures of impact and volcanic origin, and of craters produced by missile impact and explosive devices; (3) laboratory studies of the behavior of rocks and minerals subjected to shock; (4) study of the chemical, petrographic, and physical properties of meteorites and cosmic dust and development of specialized analytical techniques.

Part A, Lunar and Planetary Investigations.--The first part of the volume describes three programs: (1) lunar geologic mapping, including synoptic compilation of the mapping results at the 1:5,000,000 scale, regional mapping at a scale of 1:1,000,000, Apollo site mapping at the 1:100,000, 1:25,000, and 1:5,000 scales, and Ranger geologic mapping at a variety of scales; (2) lunar and planetary physics, including lunar photometry and polarimetry, infrared studies of the Moon and planets, research and development in application of spatial-filtering techniques to astronomical imagery; and (3) lunar engineering geology, including lunar terrain analysis and trafficability, special trafficability studies, slope-stability studies, and estimates of penetration resistance and bearing capacity.

Part B, Crater Investigations.--The second part of the volume reports progress in field and laboratory studies of craters and related phenomena. Natural impact structures have been studied at Sierra Madera, Tex.; Gosses Bluff, Australia; Flynn Creek, Tenn.; and Decaturville, Mo. Impact-metamorphosed rocks from several large impact structures are being studied in the laboratory, and shock phases of selected minerals are also being studied. Field studies of volcanic craters and related phenomena include Lunar Crater, Nev.; Fernandina caldera, in the Galapagos Islands; Diamond craters, Bend, Oreg.; Moses Rock and Mule Ear diatremes, Utah; San Francisco volcanic field, Ariz.; Nunivak, Alaska; Lava Beds National Monument, Calif., Mono Craters, Calif.; and Ubehebe Crater, Calif. Manmade craters that are being studied include missile impact craters, impact craters in sand and water, and craters made by chemical explosives.

Part C, Cosmic Chemistry and Petrology.--The third part of the volume includes reports on chemical investigations emphasizing minor element and rare earth abundances; atmospheric collections of debris believed to have been derived from the Revelstoke fireball; experimental and theoretical studies related to meteorites; and description of new facilities.

Part D, Space Flight Investigations.--The fourth, and last, part includes a summary of the final report on Surveyor television investigations, and descriptions of proposals made for manned lunar orbital and unmanned Mars and Jupiter missions.

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PART A. LUNAR AND PLANETARY INVESTIGATIONS

Lunar Mapping

During contract year 1968, as in 1967, the lunar mapping program concentrated on large scale geologic maps in support of space flight programs. The geology of each of eight prime Apollo landing sites was mapped at two scales--1:100,000 and 1:25,000. Two maps of the Ranger series were completed and submitted for publication, and two others nearly completed. In addition, three 1:1,-000,000-scale maps were published, two submitted for publication, and new versions prepared of 12 others (7 for publication, 5 for preliminary distribution). A 1:5,000,000-scale Earthside compilation was nearly completed.

Compilation at a scale of 1:5,000,000 (Contract R-66).--A geologic map of the equatorial belt--lat 32° N.-32° S., long 70° E.-70° W.--at a scale of 1:5,000,000 is being prepared for publication by Don E. Wilhelms and John F. McCauley. The map will use the ACIC orthographic LEM-1 photographic mosaic as a base. The mapping work is essentially completed, and the explanatory text is being written.

The principal result of this mapping and of concurrent mapping in the southern highlands at the 1:1,000,000 scale is an improved understanding of probable volcanic materials in the lunar terrae. Studies of Lunar Orbiter IV photographs show that materials of probable volcanic origin are more extensive and varied in the terrae than had been recognized by telescopic observations. Positive landforms of probable volcanic origin include small smooth clustered domes and large rough convex domes. Probable volcanic craters include rimmed and rimless craters of irregular outline, smooth-rimmed round craters, chain craters, irregular rings, and distinctive widened furrows. Many of these were previously considered to be deformed, eroded, or coalescent impact craters. The domes and craters described are commonly superposed on probable impact craters, suggesting that the present overall form of many craters is a hybrid produced by both impact and volcanism. Although the terrae materials are known to be generally older than those of the maria on the basis of several independent lines of evidence, many terra deposits blanket fairly young craters, suggesting that volcanic activity is in places nearly as recent as in the maria. Terra domes are generally steeper and higher than mare domes and most terra materials have higher albedo than mare materials, suggesting a compositional difference.

Mapping at a scale of 1:1,000,000 (Contract R-66).--During the period October 1967 to October 1968, progress was made toward the goal of publishing 1:1,000,000-scale geologic maps of all the quadrangles of the lunar Earthside hemisphere (tables 1-3). Three maps were published (Theophilus, Mare Vaporum, Ptolemaeus) of quadrangles in the central part of the equatorial belt of 28 quadrangles; maps of 16 of these quadrangles have been published since the program began (fig. 1, table 1). Maps of two quadrangles (Sinus Iridum, J. Herschel) outside this belt were completed and submitted for publication. Semifinal versions were prepared of seven maps being revised for publication (fig. 1, table 2). Three of these (Cassini, Macrobius, Cleomedes) are further revisions of versions prepared last year; four (Taruntius, Mare Undarum, Colombo, Rupes Altai) are the first complete versions prepared since drafted and reviewed ozalid copies were completed and distributed in 1965. Publication of these seven maps as well as the others listed in table 2 is being expedited, but publication dates cannot be predicted at the present time.

Among the uncolored ozalid preliminary maps not previously completed, three maps of quadrangles in the southern highlands (Hommel, Clavius, Schiller) were completed and are being revised for publication (table 2). Two (Wilhelm, Tycho) have been submitted for review by the authors (table 3). One map of a quadrangle in the southern highlands (Schickard) and two of quadrangles in the northeast (Aristoteles, Geminus) are less advanced but should be finished in preliminary form before October 1969. These

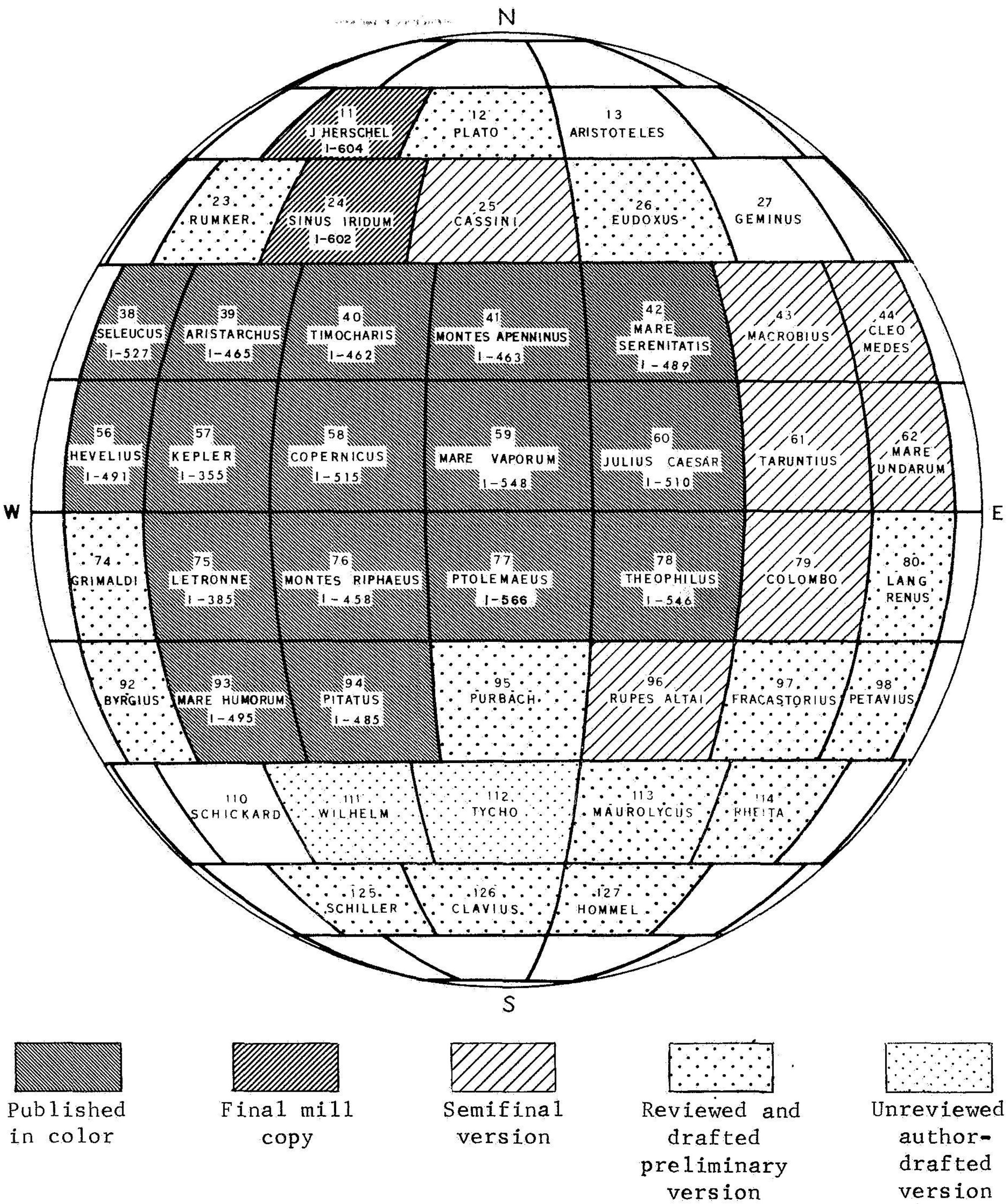


Figure 1.--Index map of Moon showing 1:1,000,000 maps available for distribution as of December 1968. Increasing density of pattern reflects progressive steps toward publication of multicolor maps.

Table 1.--Maps at 1:1,000,000 scale published or in press at end of contract year 1968 (anticipated publication dates in parentheses)

Map	Author	Number	Publication date
Kepler	Hackman	I-355	1962
Letronne	Marshall	I-385	1963
Riphaeus Mts.	Eggleton	I-458	1965
Timocharis	Carr	I-462	1965
Aristarchus	Moore	I-465	1965
Montes Apenninus	Hackman	I-463	1966
Pitatus	Trask, Titley	I-485	1966
Mare Serenitatis	Carr	I-489	1966
Hevelius	McCauley	I-491	1967
Mare Humorum	Titley	I-495	1967
Julius Caesar	Morris, Wilhelms	I-510	1967
Copernicus	Schmitt, Trask, Shoemaker	I-515	1967
Seleucus	Moore	I-527	1967
Theophilus	Milton	I-546	1968
Mare Vaporum	Wilhelms	I-548	1968
Ptolemaeus	Howard, Masursky	I-566	1968
Sinus Iridum	Schaber	I-602	(1969)
J. Herschel	Ulrich	I-604	(1969)

three are the last of the group of 44 quadrangles originally assigned, and with their completion approximately one-third of the Moon (total, 144 quadrangles) will be mapped at least in preliminary form.

Apollo site mapping (Contract T-66353G).--Preliminary geologic maps of eight prime Apollo landing sites were completed in contract year 1968. A 1:100,000-scale map of the medium-resolution Orbiter coverage and a 1:25,000-scale map of the landing ellipse

Table 2.--Maps at 1:1,000,000 scale previously completed and distributed in preliminary form and now being revised for publication. (Percentage completion considers both the authors work and reviewing; figures for some maps are therefore lower than in previous reports, where figures referred only to author's work.)

Map	Author	Percentage of revision completed: Oct. 1	Dec.
Cassini	Page	90	90
Macrobius	Pohn	80	80
Colombo	Elston	70	70
Rupes Altai	Rowan	35	50
Taruntius	Wilhelms	45	45
Cleomedes	Binder	40	40
Mare Undarum	Colton, Masursky	30	40
Plato	M'Gonigle, Schleicher	30	35
Maurolycus	Titley, Cozad	20	35
Eudoxus	Page	30	30
Petavius	Holm, Wilhelms	25	30
Grimaldi	McCauley	25	25
Purbach	Holt	20	25
Langrenus	Cannon, Wilhelms, Ryan	25	25
Rümker	Eggleton, Smith	15	20
Clavius	Cummings	0	15
Fracastorius	Tabor*	0	10
Byrgius	McCauley*, Trask	10	10
Rheita	Stuart-Alexander	0	5
Schiller	Offield	0	0
Hommel	Mutch, Saunders	0	0

*Recent reassignment.

and its immediate vicinity were prepared for each site. These 16 preliminary maps were forwarded to the Manned Spacecraft Center. Revision and standardization of the maps has concentrated on the five remaining sites of set C. Copies of these maps, without

Table 3.--Maps at 1:1,000,000 scale being prepared for distribution in preliminary form

Map	Author	Percentage of author's work completed: Oct. 1	Dec.
Tycho	Pohn	100	100
Wilhelm	Saunders, Wilhelms	100	100
Schickard	Karlstrom	75	80
Geminus	Grolier	25	45
Aristoteles	Roddy	30	30

texts or detailed explanations, were forwarded to the Manned Spacecraft Center in August 1968 for inclusion in the Apollo on-board data packages. Final versions of these 10 maps with texts and explanations are nearing completion at the time of this report. Work is also in progress on a revised and standardized version of the 1:100,000-scale map of III P-12, which includes a new landing ellipse. The status of all Apollo site maps currently in preparation is shown in table 4.

Continued study of the early Apollo sites has emphasized the differences among them. The western sites (fig. 2)--II P-13, III P-11 and III P-12--are situated on relatively young (Eratosthenian) mare material. III P-11 is especially notable in having many sinuous, discontinuous scarps suggestive of flow fronts and a widespread texture of low hummocks and hollows 5 to 10 meters across suggestive of an original volcanic topography. The scarps and texture are both indicative of relative youth. The central site, II P-8, and one eastern site, II P-6, are situated on relatively old (Imbrian) mare material. Site II P-2, the easternmost site, is situated on material interpreted to be more akin to terra material than to typical mare material. This material, termed terra-mantling material, has progressively covered typical mare material, which occurs only in a small area of the eastern part of the site. The terra-mantling material may be a young volcanic cover or fragmental debris derived from nearby rugged terra.

Table 4a.--Completed Apollo site maps. All maps have been reviewed. Final technical editing and publication will require an additional 8 to 10 months

Site*	Scale	Author
II P-2	1:100,000	Carr
II P-2	1:25,000	Wilhelms
II P-6	1:100,000	Grolier
II P-6	1:25,000	Grolier
II P-8	1:100,000	Rowan
II P-8	1:25,000	Trask
II P-13	1:100,000	Carr and Titley
II P-13	1:25,000	Titley and Trask
III P-11	1:100,000	Cummings
III P-11	1:25,000	West and Cannon
III P-12	1:100,000	Offield

Table 4b.--Apollo site maps in preparation. In most cases assignments are recent, and work is beginning

Site	Scale	Author
V-12 (Censorinus)	1:250,000	---
V-12	1:25,000	Moore
V-29 (Rima Bode II)	1:250,000	Wilhelms
V-29	1:25,000	Wilhelms
V-30 § (Tycho)	1:250,000	---
V-30 §	1:25,000	---
V-51 † (Marius Hills)	1:200,000	McCauley
V-51 †	1:25,000	McCauley
III S-23 (Fra Mauro Fm.)	1:100,000	Eggleton
III S-23	1:25,000	---
III P-11	1:25,000 (relocated)	---
III P-12	1:25,000 (relocated)	---

Table 4c.--Status of 1:5,000-scale maps for Apollo operations

Site	Mapper	Percent complete
II P-2	Stuart-Alexander	90
II P-6	West	90
II P-8	Trask	75
II P-8 (relocated)	Trask	0
II P-13	Harbour	90
III P-11	Cannon	90
III P-11 (relocated)	---	--
III P-12 (relocated)	---	--

*Preliminary geologic maps of sites II P-11 and III P-9 have been completed, but the sites are no longer being mapped because they have been dropped from the list of prime Apollo landing sites.

§ Preliminary maps have been completed at scales of 1:60,000 and 1:8,000 and appear in the Surveyor VII Mission Report.

† Maps have been completed and appear in a mission planning document, Interagency Report 5.

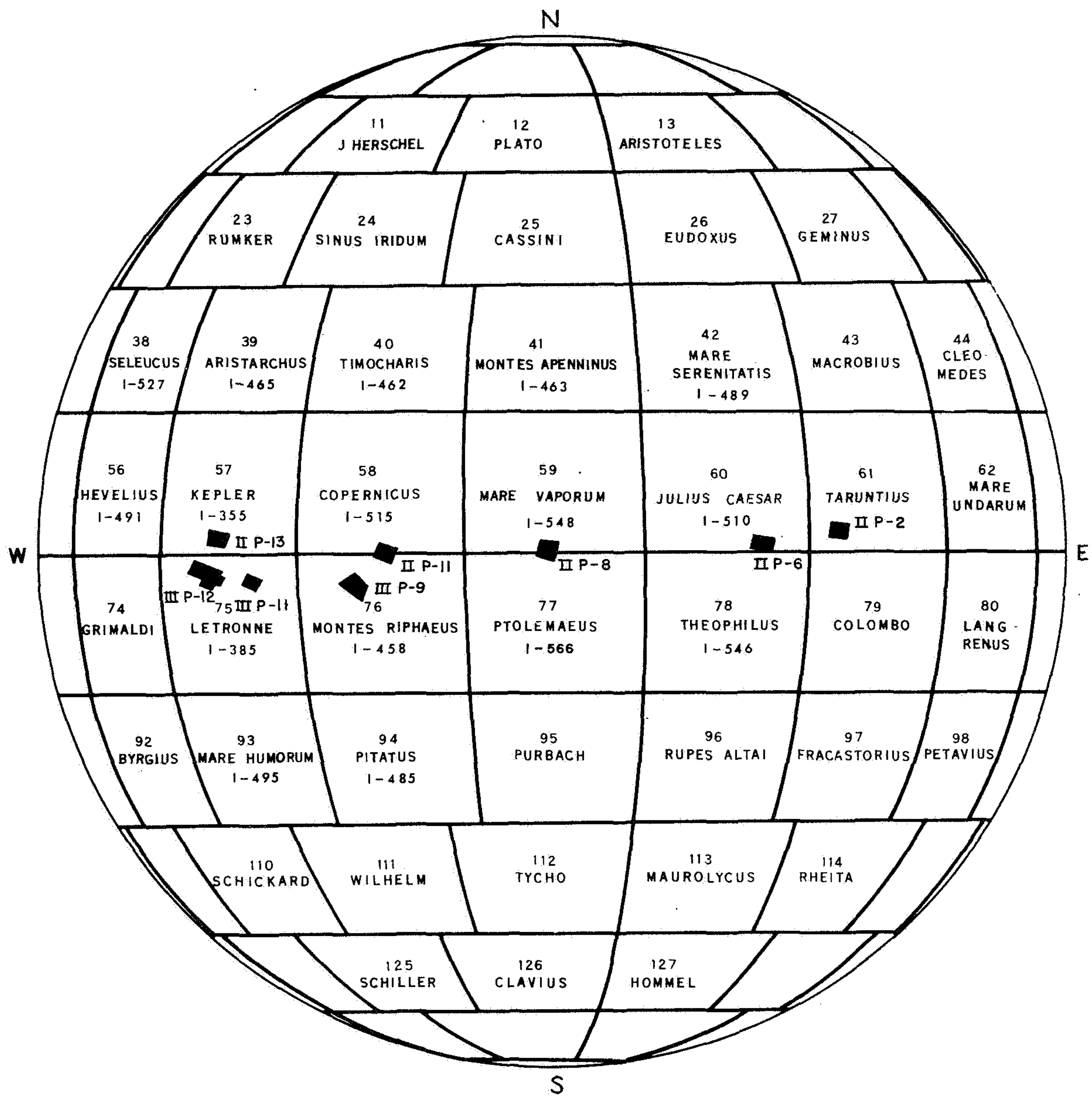


Figure 2.--Apollo sites being mapped geologically from Orbiter photographs.

During the contract year, members of the branch also worked on maps of the Apollo sites at a scale of 1:5,000 designed for use by astronauts and ground personnel during Apollo missions (table 4c).

Ranger geologic mapping (Contract WO-5171).--Two Ranger geologic maps, RLC 9 and RLC 15, were submitted for publication during contract year 1968. The authors have finished their work on the other four maps (table 5). Maps RLC 11 and RLC 14 are nearly ready to be submitted for publication.

Table 5.--Ranger geologic maps

Map*	Scale	Author
RLC 3	1:100,000	Moore
RLC 4	1:10,000	Titley
RLC 9 (I-594)	1:50,000	Trask
RLC 11	1:5,000	Cannon and Rowan
RLC 14	1:250,000	Carr
RLC 15 (I-586)	1:50,000	McCauley

*U.S. Geological Survey publication numbers in parentheses.

Three maps originally planned for publication in this series, RLC 2, RLC 7, and RLC 16, have been dropped from the project in accordance with Amendment No. 3 to NASA Defense Purchase Request No. WO-5171, dated September 27, 1968. The workload of mapping based on photographs returned by the five successful Lunar Orbiters necessitated this revision.

Lunar and Planetary Physics

Investigations of lunar and planetary physics comprise four categories: (1) lunar photometry (Contract R-09-020-041) and polarimetry (Contract R-66), (2) infrared studies of the Moon and planets (Contract R-66), and (3) research and development in the application of spatial filtering techniques to astronomical imagery (Contract T-66353G).

The 1:5,000,000-scale map of the normal albedo of the Moon, prepared from photoelectric and photographic observations made during the previous year, has been corrected and edited and will be published in U.S. Geological Survey Professional Paper 599-E. The accompanying text is a detailed discussion of the nature and reliability of the map. The photoelectrically calibrated photographic plate has now been rerun on the Beckman Whitley Isodensitracer-Joyce-Loebl Microphotometer combination at a scale of 1:2,500,000. The resulting map by R. L. Wildey, H. A. Pohn and G. E. Sutton will be published as a U.S. Geological Survey Miscellaneous Geologic Investigations Map. Several important distinctions, aside from scale, differentiate this map from the earlier one. The color-pen assembly has been used on the Isodensitracer (IDT), which virtually eliminates errors within maxima or minima surrounded by very close contours. An increase in photometric precision has been realized in the 1:2,500,000 map by increasing the number of contour intervals from 20 to 36 in the total range of the Moon's normal albedo. The resolution of the new map, as determined by the IDT aperture, is 1" of arc on the celestial sphere, three times that of the 1:5,000,000 version, and is sufficient for making an isentropic transfer of spatial information from the original astronomical plate. The positioning of the photometric data with respect to lunar coordinates has been improved (the 1:5,000,000 map used an uncontrolled mosaic base) by using a controlled mosaic having a control grid made from a computer program. Using the lunar ephemeris, the program computes the topocentric libration and transforms the system of selenographic coordinates according to an orthographic projection in the direction of the observer. The scale is determined by the topocentric lunar semi-diameter, the plate scale of the telescope, and the magnification factor of the IDT. A punched card output is used to produce the control grid on the XYZ plotter. The distortion of the orthographic projection over the exact point convergent model, in terms of the mosaic, is shown to be over an order of magnitude smaller than a resolution element, and smaller than the lunar nonsphericity which is not considered and properly distorts from ellipticity the projected intersection of the planes of constant λ or β with the lunar surface. In addition, systematic errors in photometry have been significantly reduced by the development of a method of drift correction which is more effective than the one employed for the 1:5,000,000 map. Finally, the absolute calibration has been improved by the use of revised lunar reflectivity versus wavelength, instrumental response, and solar spectrum.

A program of photoelectric observation of Surveyor landing sites, using the 30-inch Survey telescope at Anderson Mesa, was begun by R. T. Lazarus, H. E. Holt, and R. L. Wildey. Differences that may be discovered between macroscopic photometry (Earth-based astronomy) and microscopic photometry (metrization of Surveyor imagery) will probably be due to one or more of the following: (1) a difference between macroscopic and microscopic normal albedo, (2) a difference between macroscopic and microscopic photometric function, and (3) instability in Surveyor absolute calibration.

Infrared studies of the Moon revealed that Mare Crisium is as unique in its appearance as a very large region of comparative warmth on the dark side of the Moon. Crater density and age-dating based on crater rim sharpness indicate that Crisium mare material is relatively young. R. L. Wildey finds these observations consistent with the hypothesis that the surface of Mare Crisium has a higher thermal conductivity than that of other lunar regions as a result of the shorter duration of cosmic microscopic erosion and sedimentation _in situ_. Such erosion, originally hypothesized to explain infrared observations, is also suggested in other maria by gradations in the degree of angularity of the boulder-sized rocks visible in Surveyor photographs.

An infrared study of Jupiter throughout an apparition was completed by R. L. Wildey, and six Jovian brightness temperature maps have been published (Wildey, 1968b). A significant variability in the correlation of thermal and reflected image structure was found, together with evidence suggesting that the rate at which the Jovian atmosphere stores energy is often large compared with the rate at which it radiates energy. The brightness temperature of a significant fraction of the Jovian disk drops 5° to 10° K in several tens of days. The temperature of the Great Red Spot sometimes varies by as much as 2°.

Spatial filtering studies by R. L. Wildey, which were initiated to find a way of removing television scan lines without loss of image data, were extended to two new areas. In addition, an optical system for scan-line removal was designed and built. The digital approach is sufficiently more precise to warrant its application when the amount of information is not too large, as it is in lunar imagery.

The first new area of application was that of relieving the degradation of image detail that arises from atmospheric turbulence in astronomical photography. The most cogent point emerging was that photographic parameters of the original exposure must be chosen with a view towards suitability for post-exposure seeing compensation. This is especially so because the emerging criteria are diametrically opposed to the traditionally observed criteria for highly detailed photography. For spatial filtering purposes, low granularity emulsions and hence low speed are desirable; this is the reverse of normal criteria.

A second application of spatial filtering was the production of polarization imagery. The usefulness of the approach appears to be limited to celestial bodies for which all image points have the same direction of polarization, heterogeneous only in the percentage thereof, such as the Moon. Its practical use is under study.

Lunar Engineering Geology

Lunar terrain analysis (Contract T-66353G) and Trafficability (Contract W-12,388).--During contract year 1968, R. J. Pike studied the geometry of five lunar and terrestrial surfaces. Slope-frequency distributions and related statistical parameters of selected lunar terrains photographed by Lunar Orbiters II, III, and V were successfully processed using the IDT equipment and the Langley II photoclinometric computer program. Power spectral density functions of lunar terrain samples were derived using inputs from the Langley II program and terrestrial topographic data. Data on elevations, slopes, and slope curvatures were analyzed using a computer program which supplements the Langley II program. Cumulative slope-frequency curves on terrestrial data were used experimentally to approximate lunar slope distributions and test theoretical predictions for cumulative slope-frequency distributions. The relationship between the hypsometric integral and elevation-relief ratios was investigated using both lunar and terrestrial topographic data.

These studies showed significant differences between various lunar surfaces on the basis of information obtained directly from lunar photography and comparisons with terrestrial features. Such differences are apparent in slope-frequency distribution, power spectral densities, and other parameters. For example, power spectral densities of rough (western) maria may be larger by a factor of 10 or more than those of smooth (eastern) maria at a given frequency. Comparisons of lunar surfaces with natural and experimental terrestrial surfaces yield valuable insight into the nature of the lunar surface. Slope-frequency distributions and other terrain data for surfaces produced experimentally by repeated cratering, such as the crater field near Flagstaff, Ariz., and for surfaces produced by repeated impacts in the laboratory, compare well with those of lunar surfaces. Data from other terrestrial surfaces, such as the Bonita lava flow and the flanks of craters produced by explosives detonated in hard unfractured rocks, are useful in assessing the trafficability of some lunar surfaces.

Special trafficability studies (Contract R-66).--Studies by H. J. Moore of local lunar hazards that might be encountered during manned and unmanned exploration of the Moon continued during contract year 1968. These studies consider local trafficability problems associated with (1) fresh large blocky craters, (2) block fields, (3) talus slopes on walls of rilles, and (4) debris in large subdued craters. In addition, frequency distributions of craters as a function of their morphologies were studied. Profiles of craters, rille walls, and domical hills were obtained using photogrammetric, shadow measurement, and photoclinometric techniques. Frequencies of craters as a function of morphology and block frequencies of ejecta, talus, and block fields were determined using visual techniques. Some data on block frequencies around terrestrial explosion craters have been collected.

The studies show three important results. First, traverses for manned and unmanned exploration of the Moon should be planned in advance to avoid potential hazards due to blocks around some craters, blocks in talus cones, block fields, and blocks within some large subdued craters. Although it cannot be said at this time that all of these hazards are impassable obstacles, it is clear that they cannot be traversed blindly. Second, average slopes of rilles may be as high as 30° for as much as 1 km, and locally vertical slopes are present, but generally slopes are not this steep. Third, frequency distributions of craters of a given morphologic range have the same mathematical form as that for all craters where the surface has reached the "steady-state." The constants of the equations vary and are lowest for the fresh youngest craters and highest for all craters.

Slope stability studies (Contract R-66).--The influence of seismic activity on the stability of lunar slopes was investigated, and a method of indirectly evaluating lunar bearing capacities was developed. Methods of slope stability analysis that could be used in the indirect evaluation were reviewed, and stability charts, based on the "method of slices," were developed with the inclusion of horizontal seismic acceleration as one of the variables.

These studies have shown that the effects of seismic activity on the lunar surface should not be ignored when using slope stability techniques to evaluate lunar bearing capacity. From the available data, the static mass bearing capacity on the lunar surface should be at least 225 g/cm^2, and the upper limit could be as high as 4,000 g/cm^2 for footings 1 meter across. A report covering these findings is in preparation.

Penetration resistance estimates using secondary impact craters (Contract R-66).--Values of the penetration resistance obtained by H. J. Moore from lunar secondary impact craters photographed by Lunar Orbiter II are comparable to or higher than those obtained by Surveyor spacecraft. Penetration resistances for 57 secondary impact craters, computed essentially as the ratio of one-half the kinetic energy of the block and the volume of the corresponding crater, range from 1.1 to 75 $newtons/cm^2$ and average 9.6 $newtons/cm^2$. Such estimates assume an ejection angle of 45°, which yields velocities for the ejected blocks of 4 to 39 meters/sec. The ejected blocks range in size from about 1 to 9 meters across and penetrate depths of 2.6 meters and less. A second method, using the Euler equation (corrected for angle of impact), yields values ranging from 2.0 to 150 $newtons/cm^2$ and an average of 27 $newtons/cm^2$.

These values are comparable to or higher than those from the Surveyor spacecraft, which are near 3 to 6 $newtons/cm^2$ at much shallower depths (about 3 to 5 cm). The differences might arise from a number of problems inherent in the technique and available data. The calculations require estimates of block and crater dimensions, ejection angles and distances, block and target densities, and the correct association of a crater with its corresponding block. The requisites cannot always be filled because:

1. Measurements of the blocks and their corresponding craters are at best approximate when they are small and approach the resolution limit of the Orbiter photographs.

2. Ejection angles of the blocks are unknown, and data on experimental impact cratering show a wide range of ejection angles for various materials.

3. Measured ejection distances of the blocks from their primary craters are approximate.

4. Densities of ejected blocks and surface materials must be estimated.

5. Interpretations of associations of blocks and craters are sometimes ambiguous.

In addition to these uncertainties, there are no adequate data or theories describing low-velocity impact craters in terms of soil parameters. A final uncertainty arises from the fact that kinetic energies of rotation of the blocks could easily exceed the kinetic energy of translation.

Studies using Lunar Orbiter III photographs are in progress. Simultaneously low-velocity impact experiments in sand are being conducted.

Bearing capacity estimates using boulder tracks (Contract R-66).--Estimates of static bearing capacities using boulders at the end of boulder tracks shown in Lunar Orbiter II photographs yield values between 0.5 and 9.3 newtons/cm^2 for blocks between 1.4 and 8.5 meters across. Friction angles ranging from 10° to 30° were computed using Terzaghi's bearing capacity equation for circular footings, a cohesion of 10^3 dynes cm^2, a lunar γ of 220 g/cm^2-sec^2, dimensionless numbers for general shear, and measured footing radii and depths. These values are less than those reported using data collected by Surveyor spacecraft. However, the friction angle of one boulder shown in Lunar Orbiter V photograph H95 was computed to be 30°-35°, in approximate agreement with Surveyor results.

The generally low values obtained for friction angles probably result from uncertainties similar to those reported under penetration resistance estimates above. Two measurements are of critical importance in estimating static bearing capacities: (1) the contact area between the boulder and the surface, and (2) the height of the boulder. The first measurement is virtually impossible using vertical photographs. Indeed, terrestrial boulders at the end of tracks in Montana may rest on an area significantly less than one would predict from a study of the boulder or its track using vertical photographs. The second measurement is made using shadow techniques where uncertainties arise because the slope angles of the surfaces on which the shadows are cast are unknown.

Boulder tracks in Lunar Orbiter III and V photographs are currently being investigated along with studies of terrestrial boulder tracks in Montana.

PART B. CRATER INVESTIGATIONS

Natural Impact Craters
(Contract R-66)

Fieldwork was concluded at the Sierra Madera, Tex., impact structure, and was largely completed at two others--Gosses Bluff, Australia, and Decaturville, Mo. Two other probable impact craters in Australia were studied in cooperation with the Australian Bureau of Mineral Resources.

Sierra Madera, Tex.--The final report on the geology of the Sierra Madera impact structure is being prepared by H. G. Wilshire, T. W. Offield, K. A. Howard, and David Cummings. The final phases of field mapping revealed that irregular masses of mixed breccia in the central uplift are generally intrusive into the country rock. Evidence for intrusive emplacement includes steep flow foliations within the breccia, and a crude size sorting of breccia fragments such that generally finer grained breccia is concentrated in zones a few inches to a few feet wide at the edges of the mixed breccia. The Lower Cretaceous sandstone is also extensively injected, mainly into overlying Cretaceous limestone, but also into underlying Permian dolomite. In the injected sands, original crossbedding was eradicated and intricate flow banding formed, suggesting that the Lower Cretaceous sandstone was largely unconsolidated when Sierra Madera formed. Most mixed breccia, on the other hand, was formed from comminuted hard Permian rocks.

Shock-deformed quartz is present in some in-place sandstones, but extensive collections from the Gilliam and Word Formations failed to reveal any systematic pattern of distribution. Virtually all quartzose fragments from mixed breccia in the central area of the structure have well-developed multiple sets of planar structures in quartz; such structures are sporadic in breccias from the flanks of the central uplift. Some quartz with multiple sets of planar features displays asterism, an indication of permanent lattice damage.

A large mass of mixed breccia near the center of the structure yielded a number of fragments of fossiliferous chert that have well-developed complex flow banding. Large fusilinids, silicified and deformed, suggest an origin from the exposed Permian section, though chert nodules of comparble size were not observed in unbrecciated rock. Quartz in the deformed chert is completely free of the deformation lamellae that characterize other quartzose rocks from the same breccia, and this, together with the prominent flow structure, suggests that the fragments were melted and subsequently recrystallized.

The results described above lend support to the interpretation that Sierra Madera is an impact structure, as deduced from the gross structural geometry of the central uplift (Wilshire and Howard, 1968) and from shatter cone studies (Howard and Offield, 1968).

Gosses Bluff structure.--The geologic study of the Gosses Bluff impact structure, Northern Territory, Australia, was carried on by D. J. Milton, Robin Brett, and A. Y. Glikson of the Australian Bureau of Mineral Resources (B.M.R.). Fieldwork in the central zone (mapping and shatter cone measurement) was completed; mapping in the outer zone was advanced; 23 holes were drilled by the B.M.R. totaling 1,565 feet, of which 348 feet was cored; surveying of ground control for mapping and for the geophysical grid was carried out through the field season by the Department of Interior of Australia and will be completed next season; gravity measurements were begun by the B.M.R., likewise to be completed next season; an aeromagnetic survey was flown by the B.M.R.; an extensive seismic program will be carried out by the B.M.R. next season.

The central structure consists of plates of bedrock of the Stokes Siltstone (and possibly uppermost Stairway Sandstone), Carmichael Sandstone, Mereenie Sandstone, and the lower units of the Pertnjara Group, dipping steeply and facing outward. The plates are characteristically several hundred yards long, and although they show only minor internal deformation, are sharply bounded by fault zones. Mapping has shown a remarkable pattern. The structure is bilaterally symmetrical about a north-south axis, but the northern and southern halves are quite different. In the north the faults tend to run roughly north-south in the Stokes Siltstone, east-west in the Carmichael Sandstone and Mereenie Sandstone, and again north-south in the Pertnjara Group. In the south the pattern is reversed: the faults in the Stokes run roughly east-west, in the Carmichael and Mereenie north-south, and in the Pertnjara east-west. Structural details indicate that the plates have moved inward as well as from 10,000-15,000 feet upward, to lie on a shortened perimeter. The pattern of deformation apparently represents adjustment in response to this shortening, analogous in a very crude way to folding of a cloth pulled through a ring. Why the particular pattern of deformation resulted, rather than some alternative, remains an unresolved problem.

Milton with P. Fisher (B.M.R.) measured 89 shatter cones. The orientations of individual striations, an average of 20 per locality, were measured and plotted on a stereogram to portray the cone. At a few localities all striations were taken from a single physical cone; generally striations from several cone segments at one locality were combined to yield the spatial cone. At all but six localities, a single spatial cone or a cone plus a few anomalous striations was obtained, even from segments that appeared unrelated at first sight. A minority of segments belong to negative cones with apices opposed to the usual orientation. Such negative cones exactly match the complementary branch of the positive cone, indicating that cones can develop in either direction from the point of initiation and that negative cones are not produced by reflected shock waves, as has been suggested.

Cone axes lie at an angle to the bedding decreasing from over 80° near the center to 5° two miles outside the bluff. If the beds are rotated to the horizontal, cone axes point upward and generally toward a focus above the center of the structure. Some of the deviations of cone axes from a single focus clearly reflect rotation of plates in the plane of bedding during emplacement. Other deviations, however, cannot be reduced by any geometric manipulation of beds. The latter deviations indicate that, if shatter cones form normal to an advancing shock front, the shock front cannot have propagated as a simple expanding sphere but perhaps was refracted at contacts of different lithology. A computer program for handling shatter cone data is under development. Complete analysis should shed light on the mechanism of shatter fracturing, on the movement of bedrock plates during emplacement, and on the propagation of the shock pulse.

The shatter cones indicate shock propagating outward and downward from a shallow central focus at a time when the strata were approximately flat lying. At a later time (perhaps only a few seconds later) the rock that composes the bluff was drawn upward and inward. Such a history would result from a near-surface shock-producing event. It is our belief that impact is the only such event that occurs naturally.

The outer rim of the Gosses Bluff structure constitutes approximately 100 square miles of dune, gravel, and travertine-covered plain, with outcrops occurring as low hills and along creeks. Work during contract year 1968 included 2 inch-to-the-mile remapping, a search for new outcrops, and observations on breccia outcrops.

The circular structure terminates at distances from 4 to 7 miles from the center of Gosses Bluff. The boundaries of the deformed zone with the little-disturbed strata of the Missionary plain appear to be abrupt. The circular pattern around the bluff, as represented on Gemini photographs, is imparted by the travertine-covered pediment, and by the dune patterns, and does not appear to be directly related to the underlying structure. The structural pattern within the deformed zone is essentially similar to that of the central structure. The structural elements of the outer rim, however, are larger in scale than those of the central part. Thus, individual rock plates and breccia troughs are larger on the outer rim. Both elements tend to strike tangentially to the bluff, but locally deviate to radial orientations, which may correspond to the bilateral symmetry of the central structure.

The breccia troughs are interpreted as relics of the original crater breccia, caught between radially advancing bedrock plates, and subsequently buried by overturned blocks of the central uplift. The overturned plates disintegrated at their fronts into megabreccia, overlying fine crater breccia. The fine breccia in many places intrudes overlying bedrock plates. Shatter cones in the megabreccia suggest that it was originally close to the center of impact. The shock-melted flow breccia of Mt. Pyroclast overlies heated quartzitic breccia, in turn overlying normal breccia. The flow breccia does not constitute a horizontal sheet, but appears to lie over the quartzitic breccia in relief. Many blocks within the flow breccia have escaped complete melting.

The intensity of the shock at different points in the structure must be determined from the petrographic effects. Most specimens of sandstone from the bluff show the cleavage and other planar elements in quartz characteristically developed by shock, notably along the $(10\bar{1}3)$, $(10\bar{1}1)$, and (0001) planes. The specific planar elements developed in individual specimens hopefully can be correlated with the results of very recent experimental shock work to indicate the peak pressures attained at various points in the structure. Etching of polished thin sections reveals complex Dauphine twinning of quartz grains with the composition planes parallel to planar elements. The twinning is presumably shock induced, although it is apparently not known whether such twinning occurs in ordinary rock quartz.

The sandstone clasts in the suevitic breccia of Mt. Pyroclast were apparently almost completely transformed to liquid or glass, although some contain relict grains of quartz showing a high concentration of planar elements. No glass remains, and the silica has entirely recrystallized as quartz. Some of this quartz is pseudomorphous after tridymite, which presumably crystallized as the mass cooled.

As an outgrowth of the Gosses Bluff project, Milton in informal cooperation with T. Pearce of Magellan Petroleum Corp. has been examining the stratigraphy of the Mereenie Sandstone locally and has divided it into two units, possibly separated by an unconformity. The lower unit consists of light-colored uniform thin-bedded sandstone. It is tentatively considered to be of Ordovician age, as it appears entirely conformable with the Carmichael Sandstone. This unit is about 350 feet thick at Gosses Bluff and in the Gardiner Range to the south. In the Macdonell Ranges it is 50 to 100 feet thick in the vicinity of Goyder Pass, is apparently absent near Tyler Pass, and reappears and thickens westward to several hundred feet near Stokes Pass and near Deering Creek. A considerably thicker and lithologically more varied upper unit is of Devonian age, as indicated by arthrodire plates from Gosses Bluff. The base of this unit is marked by conglomerate throughout the western Macdonell Ranges and by grit with rare pebbles at Gosses Bluff. In the Gardiner Range near Areyonga the base of the upper unit is not marked by coarse material, but the lithologic distinction of the units is maintained.

Decaturville, Mo.--Preliminary work on the cryptoexplosion structure at Decaturville, Mo., showed that the structure consists of a central dome surrounded by a structurally depressed ring zone. Strata of the ring zone commonly are down-faulted more than 200 feet along a fault which appears to delimit the entire structure. Shatter cones are well developed but do not occur beyond 1,500 feet from the center of the structure. On the basis of abundant subsurface information provided by the Missouri Geological Survey, structure-contour and isopach maps were made for a large area around the structure; these show three subsurface linear features which intersect at Decaturville. Better aerial photographs have been obtained, which will greatly facilitate detailed mapping of the structure.

Liverpool and Mataranka structures.--Two circular structures of probable impact origin have been discovered in the Northern Territory, Australia, by D. J. Guppy (Australian B.M.R.) and Robin Brett. One, Liverpool Crater, is about 5 miles west of the west bank of the Liverpool River, and approximately 35 miles upstream from its mouth in Boucaut Bay, Arnheim Land. The other, Mataranka Crater, is approximately 45 miles southwest of Elsey Station, near Mataranka.

Liverpool Crater, 1 mile in diameter, consists of a rim of sandstone breccia rising to 150 feet above the surrounding plain and up to 1,000 feet wide. The breccia consists of angular blocks of sandstone apparently equivalent to the surrounding flat-lying Proterozoic sandstone and ranging in size from 20 feet downward. The breccia rests unconformably on what appears to be Proterozoic sandstone which strikes tangentially to the structure and dips at all attitudes. Microscopic planar features in quartz are similar to those produced by impact in other structures. Inside the crater, friable sandstone of probable Cretaceous age dips inward at 3°. The age of the structure, therefore, is between Proterozoic and Cretaceous.

Mataranka Crater, approximately 14 miles in diameter, involves Proterozoic sandstones and siltstones striking tangentially to the structure and dipping generally less than 45° inwards or outwards. Poorly developed shatter cones and possibly shock-cleaved quartzite are present. The structure is not continuous; it has been largely filled with flat-lying Lower Cretaceous sandstone. Inside the structure there are several outcrops up to 1 mile long of what may be devitrified suevite. The material resembles a volcanic breccia, and contains blocks of sandstone up to 20 feet long which appear mylonitic. Pronounced microscopic planar features occur in the quartz. A small outcrop of a crystalline granitic rock was also found in the interior of the structure. No other crystalline rock occurs for at least 100 miles; thus, the uplift responsible for this outcrop may be a purely local phenomenon.

Flynn Creek.--The final report on the geology of Flynn Creek Crater, Tenn., is being prepared for publication as a U.S. Geological Survey Professional Paper. The manuscript is being revised on the basis of a preliminary review and will be submitted for technical review early in 1969.

Impact Metamorphism
(Contract R-66)

In contract year 1968 research by E. C. T. Chao, O. B. James, and J. A. Minkin was directed toward systematic and detailed identification, classification, and interpretation of shock effects in rock-forming minerals, in an attempt to deduce the pressure and temperature histories of impact-metamorphosed rocks (Chao, 1968). Research covered three general areas: (1) the study of naturally and experimentally shocked tectosilicates, quartz, and feldspars, by E. C. T. Chao; (2) the study of shocked chain silicates, such as amphiboles and pyroxenes, by O. B. James; and (3) electron microscopic and X-ray single crystal study by J. A. Minkin of samples selected and studied under (1) and (2). A study of opaque minerals recovered from drill holes at Meteor Crater, Ariz., was completed by Robin Brett. D. J. Roddy continued to study the effects of shock on the crystalline structure of calcite.

James and Chao continued their detailed petrographic examination, begun the previous year, of a large collection of shocked crystalline rock samples from the Ries Crater, Germany. This study is expected to make possible a more complete and precise description of the shock effects in these rocks, to distinguish these shock effects from preexisting features, to form a basis for selecting samples for detailed chemical analysis, and to enable delineation of the most profitable directions for further research.

As a result of this work, a possible high-pressure phase of plagioclase feldspar was detected, appearing as micron-sized particles with refractive index near 1.59 embedded in thetomorphic feldspar glass. Preliminary X-ray work suggests that these particles consist of jadeite and coesite. Efforts are now in progress to concentrate and confirm the composition of this phase.

The Ries samples contain material suitable for study of the shock effects in chain silicates-minerals that will probably be significant components of lunar samples returned to Earth. Detailed studies were begun on hornblende and augite, with emphasis on the former since it is far more abundant than the latter in the samples.

The effects of shock in hornblende (as outlined by optical studies) are, with increasing shock pressure:

1. Broad smooth undulatory extinction, widely spaced deformation lamellae parallel to ($\bar{1}01$) (at this stage quartz and feldspar contain abundant shock lamellae and are partly isotropic).

2. Mosaic undulatory extinction, in part related to cleavage and fracture, fine lamellar twinning parallel to ($\bar{1}01$) (at this stage quartz and feldspar are largely isotropic).

3. Mosaic undulatory extinction, fine lamellar twinning parallel to ($\bar{1}01$), planar features (some are fractures, some are irregular planes of inclusions, some are of undetermined nature) parallel to (100) and to planes in the zones [$\bar{1}01$] and [010] (at this stage quartz and feldspar are completely isotropic).

4. Fragmentation of grains, strong mosaic extinction, lamellar twinning, and planar features as in 3 (at this stage thetomorphic feldspar glass develops vesicles along former grain boundaries).

5. Loss of green color and birefringence, grains are dusty pale brown, some grains show very fine mosaic extinction, some show abundant decorated planar features, and some show banded extinction variation (possibly in part twinning) (at this stage feldspar glass has flowed and is highly vesicular).

Preliminary results of the studies of shock effects in quartz have been published (Chao, 1968). Current investigations, using experimentally and naturally shocked quartz, are aimed at precise description and analysis of (1) features of elastic deformation such as the development of cleavages in quartz corresponding to that regime of behavior below the Hugoniot elastic limit, (2) plastic deformation or dynamic yielding without phase transition within regime I of the Rankine-Hugoniot curve above the Hugoniot elastic limit, and (3) partial phase transition of alpha quartz to vitreous silica accompanied by cell expansion of the "alpha" quartz, within regime II of the Rankine-Hugoniot curve. An additional objective is identification and analysis of the nucleation of high-pressure phases such as coesite and stishovite at peak pressures within regime III of the Rankine-Hugoniot curve where the alpha quartz or vitrified silica has been largely or completely transformed to a metastable high-pressure phase.

At present we are investigating (1) the mechanism of formation of thetomorphic silica glass without melting--a process of shock that seems to be wholly dependent on and controlled by the crystal structure; and (2) the structure of shocked quartz with expanded cell dimensions, to account for the cell expansion as a result of shock and to compare its characteristics with beta quartz and silica "O."

A cooperative study of high density feldspar glasses was undertaken by P. M. Bell (Geophys. Lab.) and E. C. T. Chao. Thetomorphic feldspar glasses of above-normal densities have been detected in shocked rocks. Annealing and densification experiments have been conducted to determine how dense glasses are formed and how density changes as a function of temperature after pressure is released. The purpose then has been to slow down the various parts of the shock-wave process for careful observation by using static techniques. The actual rate process cannot be evaluated since natural shock events probably last only a few microseconds to seconds and the actual characteristics of meteoritic impact ejecta will be influenced by many factors. Some of these factors are the characteristics of the shock wave, the release adiabat, and the particle size.

Dense plagioclase (An_{20} and An_{68}) and orthoclase (Or_{96}) glasses were synthesized statically by Bell at pressures up to 45 kb and temperatures over 1,000° C. Index of refraction of the three feldspar glasses increases linearly as a function of pressure. The indices were monitored on the experimental products for 6 months after culmination of the experiments, and no changes were observed. Therefore, the index of refraction of a glass rapidly quenched from high pressures and temperatures could be used as a secondary calibration for pressure and temperature.

After a few exploratory experiments it became evident that there are three distinct stages in synthetic annealing of dense feldspar glasses: (1) change of index during heating, (2) change of index while temperature remains constant, and (3) change of index during cooling. The first of these cannot be avoided in the experiments, although only the second and third would occur in a natural shock process. Experiments were made up to 90 seconds duration, and the effects were observed during the various parts of the annealing cycle. There is negligible index lowering in the 400°-500° C range, whereas index drops to the 1 atm value in 30 seconds at 850° C.

To evaluate the annealing effects caused by rising temperatures, the first part of the annealing cycle, rapid quenching (less than 2 sec), was applied to two materials--one An_{68}, previously synthesized at 29.6 kb, the other An_{68}, previously synthesized at 15 kb. Significant annealing occurred during the first few seconds of heating, and glass of higher density annealed about twice as fast as glass of lower density, even though both were heated at the same rate. Thus, changes in density as a function of time and of temperature are both useful parameters.

An entirely different type of annealing experiment was made at high pressures in order to study the densification process under static conditions. An_{68} glass was treated by the following procedure: (1) Glass is quenched from above the liquidus temperature at 10 kb, (2) pressure is raised to 20 kb in one set of experiments and to 40 kb in another set of experiments, (3) temperature is raised to various values below the liquidus up to 1,100° C and held for 10 minutes, and (4) pressure and temperature are quenched. A number of rather distinct features were observed. The glasses did not undergo densification below 200° C, even at a pressure of 40 kb. At both pressures density rose steeply up to 800° C, above which the index of refraction began to decrease slightly. This decrease is more notable in the 20 kb experiments.

This set of experiments shows that the density of glasses produced at high pressures will be consistent with the formation pressure. The high-pressure density will drop during annealing along uniform curves, which are temperature-dependent below the liquidus, and will rise at these temperatures if pressure is raised.

E. C. T. Chao, E. J. Dwornik and Judith A. Boreman quantitatively investigated the chemical heterogeneity of individual tektites. Schlieren of diverse composition in tektites are being analyzed with the electron probe to to establish and correlate the chemical variation with index of refraction. Since the phase shift between schlieren of different indices nearly anywhere in a tektite wafer can be measured directly, the chemical heterogeneity of individual tektites can be examined quantitatively. Preliminary results show that a high-index schlieren in a Thailand tektite is also high in silica but low in calcium and potassium and slightly low in aluminum and total iron, contrary to the bulk chemistry where the higher the bulk index of refraction of the tektite, the lower the silica content.

Thetomorphic quartz glass and nickel-iron spherules have been found in shocked ejecta from the Henbury craters of central Australia. Detailed investigations by E. C. T. Chao and J. A. Boreman of the thetomorphic quartz glass and quartz with low-index (shock) lamellae show the possible occurrence of a high-pressure phase, coesite or stishovite. Further studies are being made.

Robin Brett completed a study of the opaque minerals found in drill cuttings recovered from depths of as much as 650 feet below the crater floor at Meteor Crater, Ariz. The opaque minerals consist of meteoritic Fe-Ni, goethite, hematite, magnetite, and wüstite; samples are contaminated by drill steel. Textures indicative of melting and rapid crystallization are present. The study indicates the geochemical evidence of meteorite impact persists to depths as great as 650 feet below the present crater floor.

In a cooperative study by D. J. Roddy and T. Ahrens (Calif. Inst. Technology), a spacial sample holder has been designed to hold crystallographically oriented samples in position during passage of a single plane shock front. The sample holder is machined open after an experiment, and the shocked sample recovered with the original orientation preserved. The choice of material for the sample holder was determined by matching Hugoniots with that of the sample material. The matching techniques involved use of a computer program written to solve pressure vs. particle velocity for the materials to be used.

Experiments have been conducted with calcite crystals exposed to shock pressures from 5 to 30 kb. Preliminary petrofabric studies indicate that a significant number of $\bar{e}$ deformation lamellae are formed at the higher pressure, usually with three sets developed. The types of deformation are similar to those observed in calcite from the Flynn Creek structure in Tennessee.

Petrofabric, X-ray, thermoluminescence, infrared, and other techniques applicable to solid-state deformation will be applied to determine the types of crystalline deformation as a function of shock-wave pressure and temperature.

Volcanic Studies
(Contract R-66)

Projects dealing with volcanic craters include studies of roots of maar craters, morphology of craters formed in basalts of different types, and a caldera in a basalt shield; additional studies of volcanic rocks include lava tubes in basalts of the

Modoc field, Lava Beds National Monument, Calif., and rhyolite domes at Mono Craters, Calif. Fieldwork was concluded at the Mule Ear and Moses Rock diatremes, Utah, the Lunar Crater chain of basalt craters, Nevada, and the Fernandina caldera, Galapagos Islands. Fieldwork is well advanced at Diamond Craters, Oreg., and at a rhyolite dome in the Mono Craters field. Preliminary work was begun on lava tubes, and progress on studies in the San Francisco volcanic field, Arizona, and Ubehebe Crater, Calif., is reported.

Lunar Crater volcanic field.--Fieldwork in this area was completed in contract year 1968. A detailed map of the Quarternary basalt field and the surrounding Tertiary ignimbrites was completed by D. H. Scott as part of a Ph. D. dissertation and is available for use. This map will not be published because the area is currently being mapped at smaller scales by the Special Projects Branch; Scott's mapping will be incorporated in several of the smaller scale maps in progress. Preparation of a final report is planned for contract year 1969; it will include one or two page-sized detailed maps showing critical field relationships.

The Lunar Crater volcanic field contains a wide variety of morphologic features including cinder cones, spatter-and-cinder cones, and maars. Normal faults and other fissures provided the conduits along which the vents developed and flows were extruded. Activity apparently occurred intermittently over a strip 30 km long. The youngest flows are near the center of the strip. There is a systematic pattern to the normal faulting with a center of symmetry near Lunar Crater, suggesting a possible deep-seated intrusion at the locality. The relative ages of many of the vents can be determined in the field. Scott finds good correlation between the base-height ratio of the cones and their relative age, a relationship that should hold where mass transport only occurs down the flanks of cones and little or no material is removed at their base. This situation apparently obtains in the Lunar Crater field and may also occur on the Moon.

Ultramafic nodules are abundant in the ejecta and flows around two of the youngest cones in the field; a few small nodules have been found in ejecta on the rims of the maars. Olivine-rich lherzolite, olivine-rich wehrlite, and dunite are the most abundant rock types in the inclusion suite. Clinopyroxene-rich wehrlite, clinopyroxenite, and gabbro are also present. The lherzolite, olivine-rich wehrlite, and dunite are all strongly to intensely deformed, and many inclusions have textures found in intrusive peridotite bodies. A report on the ultramafic nodules is being prepared by N. J. Trask.

Fernandina caldera.--The caldera of the basaltic shield volcano Fernandina collapsed in June 1968. One end of the caldera floor dropped over 300 m (Simkin and Howard, 1968). The volume of collapse was 1 to 2 km^3. Violent explosions on June 11 were followed by 2 weeks of high seismic activity that apparently accompanied the collapse. Several of the earthquakes exceeded magnitude 5. Even so, the acoustic and seismic energy released was much smaller than the potential of the collapse.

The caldera floor (2.2 x 3.9 km across) dropped into a deep magma chamber along a steep elliptical boundary fault coincident with that along which the last large (prehistoric) collapse had occurred. Displacement increases from 0 at the northwest end of the ellipse to over 300 m at the southeast end, and is slightly greater away from the walls. Breakup of the floor was minor despite the large displacement. At the west edge of the floor, though, a small block of about 1/2 km^2 dropped 50-150 m as an independent unit. This small block contains a new explosion crater and numerous fumaroles, and evidently dropped into a high cupola.

The present location of most of the displaced magma is unknown. Flank eruptions on the west and south sides or under the sea may have gone unobserved, but the only extrusive materials yet recognized are a flank lava flow on May 21 and ash erupted on June 11, and their volumes are far less than that of the collapse. The Fernandina activity was contemporaneous with venting of volcanoes on southern Isabela Island, 60 km to the south.

Bend, Oreg.--The main objective of the Bend, Oreg., project is to provide a better understanding of the relationship between the morphology of volcanic landforms and their petrogenesis. Guided by this objective, preliminary geologic field investigations were begun in contract year 68 in the Diamond craters complex in southeastern Oregon, approximately 60 miles south of Burns.

Although the Diamond craters volcanic field is only 6 miles in diameter, a wide variety of volcanic landforms, such as cinder craters and cones, lava pits and tubes, maars, domes, and graben, are well exposed in varying stages of development and degrees of inundation by later volcanic materials. Thus, the Diamond craters area provides an excellent opportunity to study morphologic variations as a function of petrologic and structural character.

The Diamond craters complex is a small shield volcano built upon an essentially featureless plain. Preliminary field studies, suggest three main stages of eruptive activity. In the first stage, highly viscous basaltic lava poured out radially from a central vent. Cinders and ash covered much of this lava in the second stage, and, because these tephra deposits appear to have been ejected from the central vent, they provide an excellent stratigraphic marker. During the third, final stage, basaltic lava flowed out from local vents, many of which are older cinder craters. Doming and, in at least one case, collapse were contemporaneous with the upwelling and outpouring of this latest lava. Cinder craters and cones developed intermittently between these stages.

To date, a 7 1/2 minute quadrangle topographic map with 15 profiles in critical areas has been compiled; these data are pertinent to the morphologic studies. Compilation of the preliminary geologic map on this base is nearing completion, and petrographic and petrochemical studies are in progress.

Moses Rock diatreme.--Completion of a Ph. D. thesis on the Moses Rock diatreme by T. R. McGetchin (McGetchin, 1968a) was followed in contract year 1968 by publication of abstracts describing special aspects of the study, including a structural analysis of the breccia that indicates emplacement in a fluidized state of solids entrained in gas (McGetchin, 1968b), and an analysis of analysis of mineral relationships (McGetchin and Silver, 1968) that indicates derivation of kimberlite minerals from a significant depth range in the upper mantle--100 km or more.

Mule Ear diatreme.--Field mapping of the Mule Ear diatreme was completed in May 1968 by D. E. Stuart-Alexander, and the geology is being compiled from aerial photographs and a planetable map. The diatreme is a kidney-shaped mass with a wide outer zone of predominantly downdropped sedimentary blocks, an irregular middle zone of dikes of reconstituted sedimentary materials, and an elongate core of intrusive materials and xenoliths displaced upward from their original positions. At the present level of exposure, the core appears to be a series of pipes which are undoubtedly connected at depth and may have been connected above.

The largest sedimentary blocks in the pipe were displaced 1,770 feet stratigraphically downward in the northeast corner, 3,250 feet along the east-central zone, 4,160 feet in the northwest, and about 3,800 feet in the southwest. The downward displacement was accomplished mainly by gentle stoping because the blocks are not deformed. The areal discrepancies in amount of displacement may be due to protracted stoping in the south and west, or a later enlargement of the diatreme in the northeast.

Two minerals from a granitic xenolith in the diatreme have been dated by the fission-track technique by C. W. Naeser. The apatite fission-track age is 28 ± 3 m.y., and the sphene age is 690 ± 100 m.y. The apatite age represents the age of the diatreme, as fission tracks were totally annealed by the heat associated with emplacement of the diatreme. The sphene lost some of its fission tracks as a result of the heating. This places the temperature of the intrusion between 300° and 600° C; thus, the granitic xenolith could not have been immersed in basic magma, and the transporting and eruptive materials must have consisted of a gaseous and solid or particulate mixture. However, the age date of 28 $\pm$ 3 m.y. corresponds with the potassium-argon date of 27 m.y. reported by J. I. Ziony for a minette from the nearby Alhambra Rock, suggesting that minette magma played a role in the formation of all diatremes in this area.

Significant stratigraphic observations were made during a consulting visit by L. C. Craig, J. D. Strobell, and R. A. Cadigan. Strobell identified tuffaceous beds of the Brushy Basin Shale Member of the Jurassic Morrison Formation. The known range of occurrence of these rocks, which crop out in the San Raphael Swell, Utah, has therefore been extended. L. C. Craig stated that the diatreme is also of interest because it contains the southwesternmost occurrence of the Cretaceous Burro Canyon Formation.

San Francisco volcanic field.--Detailed comparisons of the best preserved cones and domes in the San Francisco volcanic field with features photographed by Lunar Orbiters IV and V were started in contract year 1968, and some of the results were published (McCauley, 1968b). These preliminary studies have provided new insights into the geology of the Marius Hills region of the Moon (Karlstrom, McCauley, and Swann, 1968) and into the complex morphology of the lunar terrae, now being systematically studied as part of the 1:5,000,000-scale compilation of the geology of the lunar equatorial belt.

Nunivak Island.--Studies of volcanic rocks on Nunivak Island, Alaska, were conducted in contract year 1968 by T. R. McGetchin, J. M. Hoare, and Ivo Lucchitta. Compositional relations in a micaceous lherzolite xenolith (McGetchin and Hoare, 1968) indicate that the xenolith was derived from the upper mantle. Ballistics of the Nanwaksjiak Crater were studied by K. Rohlof. Preliminary estimates of the velocity and density of the erupting basalt fluid-gas medium are in the range of 250 to 400 m/sec, and 0.001 to .009 gm/cc, respectively. G. W. Ullrich, has extended McGetchin's numerical hydrodynamic models of steady-flow in volcanic conduits to include basalt systems and to allow for the effect of gravity and other parameters. Preliminary results suggest that (1) surface fluid velocities are nearly independent of gravity for equal water content, depth, and initial temperature; (2) surface velocities are greater than the local sound speed in the medium; and (3) stable conduit shapes are divergent upward.

Lava tubes.--Fieldwork on a lava tube project was begun by K. A. Howard. Tubes form as channels in pahoehoe lava, and large collapsed tubes are similar in appearance to lunar sinuous rilles. To date, mapping at 1:5,000 scale is about half completed on four tube systems in the Modoc basalt of Lava Beds National Monument, in northeastern California. Each begins at a low-rimmed subsidence crater and is partly collapsed. One tube is 9 miles long; its gradient averages 1.25° and is less than 0.3° in its lower reaches. Another has a complex, ramifying pattern. The broadest tube found has a collapsed cross-sectional area of approximately 20,000 sq. ft. Despite a sub-horizontal cooling surface at the surface of the flow, many of the larger tubes are surprisingly narrow and deep. The mechanics of channel formation, lava drainage, and collapse of each system are being studied.

The following features are common in the lava tubes studied; their presence in lunar sinuous rilles would help to establish the origin of the rilles: (1) Many, perhaps most, tubes begin at low-rimmed subsidence craters atop low basalt shields. Others have cinder cones, spatter cones, or fissures as their source, and some tubes are only developed far from the source of their flow. (2) Tubes generally are centered on a broad low ridge corresponding to the thickest part of the flow. (3) Tubes are generally central in a flow, but late flow-unit boundaries may cross the roof of a tube. (4) Some tubes branch and rejoin complexly; on the other hand, many remain as a single channel throughout their length. (5) Tubes seldom collapse completely, so that bridges of intact roof are common between trench segments. (6) Up-tilted rims surround some tube collapses. (7) Longitudinal ridges are common inside trenches that are collapsed tubes; they represent hogbacks of inward-tilted slabs broken away from the wall.

Volcanic domes.--As part of a comparative study of lunar and terrestrial volcanic domes, E. I. Smith mapped a rhyolite dome in the northern part of the Mono Craters chain, California, for a doctoral dissertation at the University of New Mexico. Research is also being conducted to develop criteria for the recognition of volcanic domes on the lunar surface and to determine lunar dome distribution.

The rhyolite dome, mapped during the summer of 1968, is 1,200 feet in diameter at the base and 200 feet high. A terraced explosion crater 600 feet in diameter and 150 feet deep is present at the summit. The petrofabrics and petrography of the dome rocks are now being studied. Preliminary results indicate that: (1) The gross structure, based on foliation, is that of a funnel tilted to the east. (2) There are two main sets of fractures: one concentric with the crater rim dipping outward and one radial to the crater dipping at high angles. These fracture sets are probably related to the crater-forming event. (3) Abundant alkali feldspar microlites are strongly alined in the direction of flow. Small amounts of biotite and opaque material are also present. The groundmass is a strongly flow banded, highly vesiculated glass showing textural differences between the broader flow bands; these differences include the density of microlite packing, discontinuities of feldspar orientation at band interfaces, and a decrease in the degree of vesicularity in denser bands.

Preliminary work suggests that small to intermediate sized (less than 3 miles diameter) terrestrial impact and volcanic craters can be distinguished on the basis of their log depth to log diameter relationship. Applying this relationship to the summit pits of lunar domes will aid in recognition of volcanic domes. Lunar Orbiter photographs are being surveyed to determine the distribution of volcanic domes. Over 100 new domes have been discovered thus far.

Ubehebe Crater.--Many samples of shattered and fractured quartzite wallrock from Ubehebe Crater, a volcanic feature, were examined with a universal stage microscope. Deformation features of the types observed at meteorite impact craters were looked for but none were found, which suggests that pressures generated during formation of this crater were less than those at meteorite impact sites of comparable size.

Missile Impact Craters
(Contract R-66)

Eight missile impact craters and eight explosion craters were mapped (data tabulated below), and passive seismic studies were continued. The results of remote sensing studies were reported

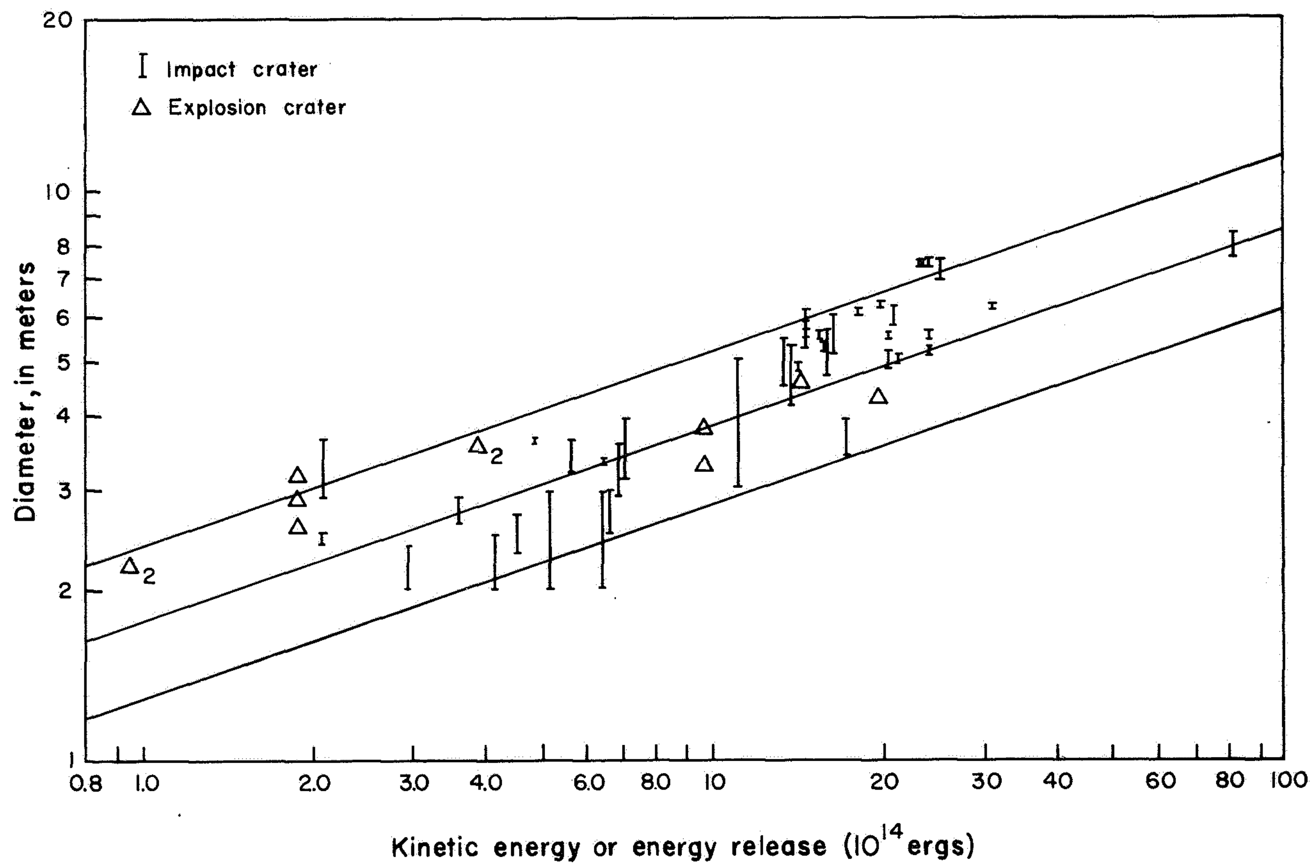
Missile impact craters

	Target	Target density (g/cm^3)	Kinetic energy (10^{14} ergs)	Impact angle	Rim diameters (meters)	Moisture content (in percent)
1.	Alluvium, gypsiferous	1.36	14.4	47.5°	5.4-6.0	≈5
2.	Sand, gypsum	1.35	14.4	47.5°	5.2-6.2	≈7
3.	Do.	1.35	14.4	47.5°	5.8-6.2	≈7
4.	Gypsum lake beds	≈1.98	6.45	oblique	3.28	≈6-7
5.	Alluvium with substrate of coarse debris	1.54	2.09	60.6°	2.4-2.6	≈5
6.	Gypsum lake beds	1.85	23.2	46.2°	7.3-7.4	6-7 near surface. 12-13 at depth of a few meters
7.	Do.	1.80	24.1	46.2°	7.2-7.5	Do.
8.	Do.	1.80	23.5	46.2°	7.3-7.4	Do.

Explosion craters

	Target	Target density (g/cm^3)	Charge weight (lb)	Depth of burial (cm)	Approximate energy release (10^{14} ergs)	Rim diameter (meters)
1.	Alluvium with substrate of coarse debris[1/]	1.54	5	25	0.95	2.2-2.3
2.	Do.	1.54	10	16	1.9	2.2-2.7
3.	Do.	1.54	10	33	1.9	2.8-2.9
4.	Do.	1.54	10	66	1.9	3.2-3.3
5.	Do.	1.54	20	41	3.8	3.5-3.6
6.	Do.	1.54	5	25	0.95	2.2-2.3
7.	Alluvium, clayey	2.07	75	102	14.0	4.5-4.7
8.	Alluvium with some coarse fragments[2/]	≈1.5	20	48	3.8	3.4-3.7

[1] Same material as that in which crater No. 5 was excavated by missile impact.
[2] Material similar to that of explosion craters Nos. 1-6.



Comparison of kinetic energy with crater diameter in explosion and missile impact craters.

(Moore, Kachadoorian, and McCauley, 1968), and a report describing the results of studies of trenches cut through four craters was prepared. The accompanying graph compares kinetic energies of missiles with the diameters of the craters they produced, and energy releases of explosives with diameters of explosion craters. Assistance in detonating the explosives and data on the kinetic energies and angles of impact of the missiles were furnished by the Commanding General, White Sands Missile Range, N. Mex.

A missile impact was used to test passive seismic equipment designed for use on the Moon. The test, which was conducted by Dr. G. V. Latham of Lamont Geological Observatory, Columbia University, Palisades, N.Y., was successful. The explosion craters mapped were produced during calibration of the equipment. These tests will continue using new light-weight equipment.

Additional evidence was obtained on the relation between water content and size of craters in porous target materials. The same missiles produce larger craters in wet target materials than in dry. Crater volumes in targets containing about 25 percent water are about six times larger than in dry materials; crater volumes in targets containing about 12 percent water are several times larger than in dry materials.

Differences in sizes of craters in wet and dry materials probably result from differences in compressibility and positive pore pressures which reduce the effective strength of the target. These differences are reflected in the morphology of the craters and in their ejecta. Craters in wet target materials have a continuous rim, and their ejecta contain few to no fragments of compressed target material. Craters in dry porous target materials are rimless on the "up" trajectory side (side from which the missile comes) and fragments of compressed target material are abundant in their ejecta. Such evidence suggests that irreversible energy losses resulting from compression might be lower for wet targets than dry targets. The effective strength of wet target materials is substantially reduced because of positive fluid pressure that develops due to impact, and the resulting crater is larger than it would have been if the material were dry. Thus, both irreversible heat losses and fluid pressures could account for the size differences of impact craters in wet and dry targets.

Experimental Impact Investigations

Impacts with sand.--Studies of vertical impacts of long rods with fine sand at velocities between 200 and 700 cm/sec show that the dynamic resistance is proportional to the penetration of the projectile. Time-penetration histories, recorded by a high-speed camera, may be divided into two parts: (1) an initial period characterized by a large transient deceleration, and (2) a final period characterized by a linear increase in deceleration to the final penetration depth. The deceleration of the penetrating rod during the final period is consistent with previous experimental data on penetration and earlier interpretations of data on impacts of low-velocity rods with sand (Moore, 1967).

Initial large transient deceleration becomes more important, however, at higher velocities and for impacts of short rods or spheres. For this reason, impacts of spheres with sand are being investigated. Preliminary studies of impacts of 21-cm diameter cement spheres with sand at velocities between 100 and 1,080 cm/sec indicate that the ratio of the kinetic energy at impact to the volume of the sand displaced is directly proportional to the impact velocity at the highest velocities and nearly constant at the lowest velocities. The magnitude of the ratio of kinetic energy to volume displaced at the lowest velocities is nearly the same, but slightly less than, the static bearing capacity computed using Terzaghi's bearing capacity equation. Further work is being conducted to appraise the effect of sphere size for low-velocity impacts.

Water-drop craters.--Studies of transient craters produced by water drops falling on water show that significant amounts of energy are present as kinetic energy in a cylindrical wave which surrounds the crater when it has reached its maximum size. At maximum size, about 80 to 90 percent of the initial drop kinetic energy can be accounted for as potential energy, surface energy, and kinetic energy of the outwardly expanding cylindrical wave. The energy partitioning changes with velocity and crater size. For craters produced by 14 milligram drops with velocities near 155 cm/sec, surface energy is the most important energy sink; whereas potential energy is the most important energy sink at velocities near 566 cm/sec. The percentage of kinetic energy in the cylindrical wave increases with increasing drop velocity and may exceed that of surface energy for the highest velocities.

Explosion Crater Investigations

Chemical explosion craters in alluvium at the Suffield Experimental Station, Alberta, are being studied by D. J. Roddy and personnel of Canada's Defence Research Establishment.

Distant Plain 6 crater.--Detonation of a 100-ton TNT sphere tangent to the ground surface formed a crater about 30 m in diameter and 5.5 m deep in unconsolidated flat-lying alluvium and lacustrine sediments. A well-defined central mound about 2 m high occupied the entire crater floor and contained beds structurally uplifted 3 to 5 m. Excavations showed that the internal structure of the mound was nearly identical with that in a 100 m diameter crater (Snowball) produced by a 500-ton TNT hemisphere. Rim uplift and faults and folds concentric to the crater are comparable in position and type to deformation in the rims of Flynn Creek Crater. Most of the ejecta and fallback consist of sheared blocks produced by compression of the upper meter of soil. A final report and geologic map have been completed and will be submitted for publication upon final clearance by the U.S. Government.

Prairie Flat crater.--Detonation of a 500-ton TNT sphere tangent to the ground surface produced a crater with a broad, flat central uplift, concentric ring folds on the crater floor, rim folding accompanied by high- and low-angle faults, a large overturned flap, and a continuous ejecta blanket. The crater is about

61 m in diameter and about 5 m deep. The structural and topographic configuration is remarkably similar to certain large terrestrial impact craters. Geologic mapping has defined the major ejecta types and units, asymmetries of the ejecta blanket, and the associated fireball burn pattern. Fused clay particles were formed from the soil horizon immediately below the TNT charge and were distributed as fallout. Pervasive fracture systems beneath the crater floor allowed water to flow to the surface and localize sand cones that partly filled the lower part of the crater. The original ground surface now dips 20° to 30° toward the crater. A large overturned flap overlies the rim and contains continuous units of interbedded sand and clay lying in an inverted position; this extends for a crater diameter (61 m) from the crater rim as a hummocky unit.

PART C. COSMIC CHEMISTRY AND PETROLOGY

Chemistry of Cosmic and Related Materials
(Contract R-66)

The efforts of this project have been devoted mainly to the following: (1) Collaborative and independent chemical investigations and research relative to crater investigations, impact metamorphism, volcanic studies, geochemical characteristics of the mantle, meteorites, tektites (emphasis on minor and rare earth abundances as clues to the origin of parent materials, i.e., igneous or sedimentary), and geochemistry of magmatic differentiation; (2) strengthening and broadening the Branch's microchemical capability and potential, particularly in the areas of X-ray fluorescence spectroscopy, emission spectroscopy, atomic absorption spectrometry, gas chromatography, and radioactivation analysis; and (3) invited contributions to reference textbooks.

Variation of geochemically coherent pairs in igneous suites were studied by D. L. Gottfried, L. P. Greenland, and E. Y. Campbell (1968). Concentrations of Nb, Ta, Zr, Hf, Th, U, and Cs have been determined in samples of igneous rocks representing the diabase-granophyre suites from Dillsburg, Pa., and Great Lake, Tasmania.

Niobium and tantalum show a three to fourfold increase with differentiation in each of the suites. The chilled margin of the Great Lake intrusion contains half as much niobium and tantalum (5.3 and 0.4 ppm, respectively) as the chilled basalt from Dillsburg (10 and 0.9 ppm, respectively). The twofold difference between the suites is correlated with differences in their titanium content. The average Nb/Ta ratios for each suite are similar: 13.5 for the Great Lake suite, and 14.4 for the Dillsburg suite.

The zirconium content of the two suites is essentially the same and increases from 50-60 ppm in the chilled margins to 240-300 k ppm in the granophyres. Hafnium content is low in the early formed rocks (0.5-1.5 ppm) and achieves a maximum in the granophyres (5-8 ppm). The Zr/Hf ratio decreases from 68 to 33 with progressive differentiation.

In the Dillsburg suite, thorium and uranium increase from 2.6 and 0.6 ppm, respectively, in the chilled samples to 11.8 and 3.1 ppm in the granophyres. The chilled margin of the Great Lake suite contains 3.2 ppm thorium and 9.8 ppm uranium; the granophyre contains 11.2 ppm thorium and 2.8 ppm uranium. The average Th/U ratios of the Dillsburg and Great Lake suites are nearly the same--4.1 and 4.4, respectively. Within each suite the Th/U ratio remains quite constant.

Cesium and the K/Cs ratio do not vary systematically in the Dillsburg suite, possibly because of redistribution or loss of cesium by complex geologic processes. Except for the chilled margin of the Great Lake suite, the variation of Cs and the K/Cs ratio are in accord with theoretical considerations. Cesium increases from about 0.6 ppm in the lower zone to 3.5 ppm in the granophyre; the K/Cs ratio ranges from 10×10^3 in the lower zone to 6×10^3 in the granophyre.

A comparison of the abundance of some of these elements is made with those reported on oceanic tholeiites from the Atlantic and Pacific Oceans. Trace elements with large ionic radii (Th, U, Cs) are present in significantly greater concentrations in the two continental tholeiitic series than in the oceanic tholeiites. However, this does not seem to be true for lithophilic elements of smaller ionic radii (Zr and Nb). These trace element distribution patterns, when considered with other minor element and isotopic studies, indicate that (1) crystal contamination does not entirely account for differences between continental and oceanic tholeiites, and (2) the oceanic tholeiites do not necessarily delimit the geochemical characteristics of the mantle.

Phosphorus, with an abundance of 0.X weight percent in basalts, is strongly concentrated in the residual liquid relative to silicate and oxide minerals and provides a direct measure of the amount of crystallization of basaltic liquids, as found by A. T. Anderson and L. P. Greenland (1968). Phosphorus contents of phenocrysts and glass or groundmass from Hawaiian subalkaline basalts, determined by neutron activation and electron microprobe analysis, yield the following fractionation factors (P in glass of groundmass/P in mineral): Olivine = 30, Pyroxene = 140, plagioclase = 60, ilmenite = 20. Modal proportions of these minerals indicate a bulk fractionation factor of about 80. These factors are large enough so that the factor by which phosphorus increases in the liquid during fractional or equilibrium crystallization is numerically closely equal to the reciprocal of the fraction of liquid remaining.

Phosphorus fractionation factors provide a basis for quantitative comparison of the variation of major and minor elements during the crystallization of various basalt liquids. Other measures of crystallization, such as the mafic index, do not permit such comparisons because they are affected by changes in the composition of the liquid.

A combined chemical X-ray fluorescence method was described by H. J. Rose and F. Cuttitta (1968a) for determining rare-earth elements in small amounts of complex rare-earth minerals and materials of astrogeologic interest. These elements yield a complex X-ray spectrum in which many of the analytical emission L_α lines of a given element coincide with the L_β and(or) L_γ lines of a lighter rare-earth element several atomic numbers removed. The proposed analytical scheme corrects for these interferences. Sixteen elements consisting of the lanthanides, yttrium, and scandium can be determined on as little as a 1-mg portion of the separated oxides. The oxides are dissolved in 1 ml of dilute acid, absorbed onto cellulose powder, and pressed into a pellet for X-ray excitation. Chemically analyzed geologic standards are not required for calibration.

Comprehensive and accurate data on the relative and absolute abundances of the elements are critical to a better understanding of the principles governing their crustal distribution and migration processes. Many geochemically coherent pairs or groups of elements (e.g., the halogens and the rare earths) are difficult to determine chemically. Microanalytical methods combining chemical and X-ray fluorescence techniques have been developed [F. Cuttitta and H. J. Rose (1968)] not only to determine these elements rapidly and accurately, but also to provide total analyses of milligram quantities of rare extraterrestrial and terrestrial specimens. One of these methods (solution-dilution) is virtually free of matrix effects and is adaptable to the analysis of trace or major constituents. These methods have proven invaluable in the microdetermination of Sc, Y, and the individual rare-earth elements in minerals or rare-earth separates on as little as 1 mg of total sample. Other applications have been the determination of iron in silicates of astrogeologic interest, and total analysis of small amounts of chromium, sulfide, and carbonate minerals.

A new approach to solving matrix problems in X-ray fluorescence analysis of trace elements has been applied by F. Cuttitta and H. J. Rose to bromine in saline waters and zinc in silicates. The method requires no prior knowledge of the chemical composition of the sample. Marked matrix effects are minimized by dilution, and the problem of variable backgrounds due to residual matrix effects is solved by using a slope-ratio technique. The slope of a standard curve prepared from pure solutions is compared with that of spiked samples. The ratio of the slopes permits the calculation of an adjusted background which does not significantly differ from that of an absorbent impregnated with the sample matrix free of the element sought. The excellent agreement of the zinc and bromine data with analytical results obtained by other methods suggests that the technique can be used for determining other trace constituents in terrestrial and extraterrestrial materials. Application of the slope-ratio technique to other modes of instrumental analysis appears feasible.

A neutron activation procedure suitable for the routine determination of tantalum and hafnium in silicates was described by L. P. Greenland (1968b). The irradiated sample is fused with sodium peroxide and leached, and the insoluble hydroxides are dissolved in dilute hydrofluoric acid-hydrochloric acid. After LaF_3 and AgCl scavenges, tantalum and hafnium are separated by anion exchange. Tantalum is obtained radiochemically pure; ^{233}Pa and ^{95}Zr contaminants in the hafnium fraction are resolved by gamma ray spectrometry. The chemical yield of the procedure is determined after counting by re-irradiation. Values for the eight U.S. Geological Survey standard rocks were reported.

A fast coincidence-counting technique has been used by L. P. Greenland (1968a) to simplify the determination of cobalt and cesium in silicate rocks. After neutron irradiation, Co^{60} activity is counted directly in the sample with no chemical separations. Cs^{134} activity is counted after a rapid chemical separation from scandium. Analyses of eight U.S. Geological Survey standard rock reference samples by this technique have been presented.

Tektite Analyses.--Out of 112 high-precision chemical analyses of tektites, 70 were selected from the Australasian strewn field. Each tektite is analyzed for 11 major oxides (SiO_2, Al_2O_3, Fe_2O_3, FeO, MgO, CaO, Na_2O, K_2O, TiO_2, T_2O_5 and MnO), and 21 minor elements, (Pb, Ag, Cu, Ga, Cs, Rb, Li, Mn, Cr, B, Co, Ni, Ba, Sr, V, Be, Nb, Sc, La, Y, and Zr). The analyses were made by Frank Cuttitta, M. K. Carron, and C. S. Annell. The chemical data are being reduced and analyzed statistically by A. T. Miesch and John Conner, and will be interpreted by E. C. T. Chao and these contributors. Among the samples analyzed, 8 javanites and 2 australites of high specific gravity were submitted for analysis by Dean Chapman.

The 70 new analyses show that among the Australasian tektites, various chemical groups can be distinguished:

		MgO/SiO_2 x 100	CaO/SiO_2 x 100	MgO/CaO
Thailand tektites	(12)	2.34-3.11	2.31-2.88	0.94-1.23
Indochinites	(18)	2.89-4.24	2.39-2.78	1.11-1.58
Philippinites	(17)	2.66-4.13	3.73-5.55	0.49-1.04

		MgO/SiO_2 x 100	CaO/SiO_2 x 100	MgO/CaO
Javanites	(15)			
Group A		3.87-5.24	3.03-4.03	1.10-1.36
Group B		4.95-12.34	3.56-5.81	1.39-2.77
Australites	(8)			
Group A		1.72-2.40	2.87-4.05	0.59-0.75
Group B		2.32-2.72	5.38-7.81	0.31-0.48
Group C		5.99-6.71	5.08-7.46	0.80-1.32

The selected Thailand tektites with 71.1 to 74.4 wt. percent silica are characterized by a nearly equal amount of low magnesia and lime. The analyzed indochinites with 72.3 to 76.5 wt. percent silica are characterized by greater magnesia than lime. Most of the selected philippinites with 69.1 to 74.2 wt. percent silica are characterized by greater lime than magnesia. One philippinite has lime content in excess of 4 wt. percent. The javanites with 64.5 to 74.4 wt. percent silica are higher in magnesia than lime: one group is low in magnesia (2.88 to 3.79 wt. percent) and high in K_2O (2.17 to 2.29 wt. percent), whereas another group is high in magnesia (3.61 to 7.95 wt. percent) and low in K_2O (1.34 to 2.10 wt. percent). Among the few australites analyzed (63.0 to 78.0 wt. percent silica) one group is low in lime and magnesia, particularly magnesia; one group is high in lime (in excess of 4.0 wt. percent); and a third group, high in both magnesia and lime. One australite analyzed contains 3.85 wt. percent Na_2O, which is similar to the Ivory Coast tektites but unique for Australasian tektites. The parameter that varies the least among the Australasian tektites is the Na_2O-to-K_2O ratio (0.4 to 0.8). The high magnesian Australasian tektites are also characterized in general by high Ni, Co, and Cr.

We failed to find any terrestrial rock that is similar to those Australasian tektites with high silica, low alkali (K_2O

greater than Na_2O) and magnesia greater than lime. It is inconceivable that these tektites could have been derived from a terrestrial basalt or basaltic parentage. Those Australasian tektites with calcium greater than magnesia, however, are similar to a rare type of alkalicalcic granite with low alkalis. Extensive volatilization alone cannot account for the observed chemical variations, particularly in those that contain either high magnesia or high lime. Wherever they are originated, these various chemical groups represent a variety of rock types, if not varieties of two major rock types.

Controlled investigation of chemical inhomogeneities of individual tektites was carried out by E. C. T. Chao, George Desborough, and E. J. Dwornik. The investigation employs the combined use of interference microscopy and electron microprobe analysis. The method is far superior to any previously tried method of separation and analyzing the separated portions of an individual tektite.

A detailed quantitative survey of the index of refraction of any point of interest of a tektite wafer can be determined by interference microscopy. The wafer is cut normal to the schlieren with plane-parallel polished surfaces and its thickness precisely measured. Areas of continuous and discontinuous index variation are clearly revealed. Areas of contrasting index of refraction or of maximum difference can by pinpointed for analysis by the electron probe.

Low-index glass inclusions and high index glass inclusions have been studied by this combined method. In addition, investigation of the heterogeneous chunky Thailand tektite known as the Muong Nong type shows that light-colored bands containing abundant frothy lechatelierite inclusions are actually higher in index than the adjacent more brownish glass with fewer inclusions. In sharp contrast with that of the bulk composition, the chemical variations are complex and cannot be predicted on the basis of the index of refraction.

Electron probe analysis of a low-index glass inclusion (n = 1.4994) in a Thailand tektite imbedded in the matrix glass on either side (n = 1.5090 and n = 1.5059) shows that it is higher in silica by 3.3 wt. percent accompanied by lower Al_2O_3, total iron, MgO, and CaO.

Electron probe analysis of several recently discovered high-index glass inclusions in a javanite shows that the high-index glass inclusions are lower in silica content than the matrix glass by 2.1 to 4.0 wt. percent and higher in total iron by 2.1 to 2.4 wt. percent and higher in MgO by 2.4 to 2.7 wt. percent. One of the inclusions is unique in that it contains as much as 8.7 wt. percent MgO and 63.3 percent SiO_2 and still with K_2O (1.2 percent) greater than Na_2O (0.5 percent) and high alumina content (11.4 percent). These high-index inclusions contain the greatest amount of MgO and total iron among all land tektites investigated. Such inclusions help to bridge the gap between chemical composition of the land tektites and the deep sea microtektites.

We believe that the low-index and the high-index inclusions represent fused parent rock types. Such chemical variations represent a clear-cut range of chemical type of source material. Based on their mode of occurrence, we conclude that these inclusions are not results of change by volatilization. We believe that such inclusions are evidence of incorporation of one rock type captured by another during the fusion and ejection process. We do not believe that the inclusions were fused in situ.

The heterogeneity represented by lenticular banding or layering is evidence of inhomogeneity in the starting material. The chemical composition of such complex heterogeneity cannot be predicted on the basis of the index of refraction. This feature is most pronounced among the chunky Thailand tektites.

It seems evident that controlled investigation of the chemical heterogeneity is a basic requirement for the interpretation and understanding of tektite genesis. We believe that the discovery of high-index inclusions in javanites strengthens the prediction that the parent materials of the basic end member of the magnesian clan of Australasian tektites are characterized by low alkalis, high magnesia and alumina and moderate-to-low silica. If tektites are of lunar origin, we should not be surprised to find such materials among the returned lunar samples. The same prediction applies to the high-calcium types found in Santa Mesa in the Manila area of the Philippines. Such compositions are not inconsistent with the alpha back-scattering data of Surveyors V, VI, and VII.

Invited contributions to reference textbooks were prepared by Irving May and F. Cuttitta (1967) and by H. J. Rose and F. Cuttitta (1968b).

Petrology of Meteorites
(Contract R-66)

Progress on studies of the petrology of meteorites included an experimental study of melting relations in Fe-FeS mixtures and theoretical examination of an Earth model in which the core and mantle formed in equilibrium, both of indirect application to meteorites. Chemical analyses obtained by Surveyors V, VI, and VII were compared with analyses of howardite and achondrite meteorites, for which a lunar origin has been proposed. Major element analyses of previously unstudied achondrites were begun. These analyses, as well as size-frequency studies on breccia fragments in achondrites, will continue.

The melting relations of Fe-FeS mixtures covering the compositional range $Fe_{100}S_0$ to $Fe_{67}S_{33}$ have been determined at 30 kb pressure by Robin Brett and P. M. Bell (Geophys. Lab., Carnegie Inst. of Washington). The phase relations exhibit behavior much closer to ideality than at 1 atm. The eutectic consists of $Fe_{73.5}S_{26.5}$ at 990° C. Solubility of S in Fe at elevated temperatures at 30 kb is of the same order of magnitude as at 1 atm. Interpolation of the 1 atm and 30 kb liquidus curves gives values of $\frac{dT}{dP}$ ranging from 2.3° C/kb to 7.0° C/kb, depending on the composition. The study has bearing on the temperatures within the metallic cores of planetary bodies if they contain sulfur, since the pressure of sulfur considerably lowers the melting temperature with respect to pure iron. The effect is more pronounced at 30 kb than at 1 atm.

Brecciated achondrites not previously analyzed will be studied during the next year. The study will include electron microprobe analyses for determination of the range of composition of pyroxenes and plagioclases. Size-frequency studies will be made of brecciated fragments to investigate possible correlations with size-frequency distributions of fragments in blocks photographed by Surveyor television.

Robin Brett finds that if certain assumptions are granted, the core of a chondritic Earth model should contain Fe with Si (10-25 wt percent), a little Ni (no greater than 5 wt percent), and about 1 wt percent of Cr and Mn. The assumptions are as follows: Fe + (Mg/Si) in the Earth's mantle is greater than unity, and Fe + (Mg/Si) for the Earth as a whole is greater than or equal to 1.65.

A. E. Ringwood and others have proposed that the core has never been in chemical equilibrium with the mantle. Brett finds that the arguments on which this conclusion is based are incorrect or need not necessarily apply. The data presently available, sketchy as they are, support an Earth model in which the core formed in chemical equilibrium with the mantle, and maintained this equilibrium.

M. B. Duke compared the chemical analyses obtained by Surveyors V, VI, and VII with data for eucrite and howardite achondrite meteorites, for which he has proposed a lunar origin. Data collected from mare sites by Surveyors V and VI closely resemble eucrites in composition, consistent with the proposed model in which eucrites are derived from the maria. The Surveyor VII analysis, of an atypical upland region, does not match well with the composition of the howardites, considered by the model to represent fragmental aggregates of upland rocks. However, the Surveyor VII analysis is consistent with the composition of rocks that can be inferred to be constituents of the howardites. More accurate elemental determinations, especially the sodium contents of the Surveyor analyses, are required before a wide variety of proposed analogs, including the meteorites, can be further reduced.

M. B. Duke planned and monitored the early stages of construction of an ultraclean laboratory facility in Washington, D.C. The laboratory, which is of the laminar-flow type, will provide dust-free temperature- and humidity-controlled work areas for sample preparation, chemical analysis, physical property determination, and optical microscopy. Atmospheric dust will be almost entirely absent in the laboratory, which will be pressurized with respect to the outside environment; specifications require the particle count to be less than 100 per cubic foot (particles greater than 0.3 microns), compared with tens of millions per cubic foot in ordinary air. Personnel entry will be controlled, in order to reduce contamination from body and clothes. The laboratory will provide an ideal facility for Duke's proposed analysis of returned lunar particulate material.

Cosmic Dust
(Contract R-66)

In contract year 1968 cosmic dust studies concentrated on examination of atmospheric collections of particulate debris believed to have been derived from the Revelstoke fireball of March 31, 1965. The debris examined was collected on airborne filters flown approximately 3 days after the event at a considerable distance downwind from the path of the fireball. The filters contained an unusual assemblage of particulate materials, quite distinct from collections made under normal conditions. The most obviously anomalous characteristic is the large concentration of magnetic spherules, especially those less than 10 μ in diameter. X-ray and microprobe analysis showed that the spherules consist of a very pure magnetite. Also present in comparable numbers are glass spherules. They are composed largely of silicon and aluminum with lesser amounts of iron and potassium and trace amounts of nickel. In addition to the spherules are many irregularly shaped particles, mostly opaque and either glassy or microcrystalline. Approximately 20 percent of the opaque particles analyzed by the microprobe contains more than 10 percent nickel. In some, nickel was the only element detected; in others, only nickel and sulfur were detected or the particle appeared to be a mixture of nickel and silicate materials. Most of the particles are in the 10 to 20 μ size range, making X-ray analysis marginal. Patterns have been obtained for some of the particles, but these have eluded interpretation.

Revelstoke is a carbonaceous chondrite. The composition of the particles is difficult to reconcile with this type of meteorite. Revelstoke contains only minor amounts of nickel and aluminum, but the glass spherules are rich in aluminum and many of the irregular particles are rich in nickel. The peculiar chemistry of the particles may result from selective ablation of different components of the meteorite during passage through the atmosphere.

PART D. SPACE FLIGHT INVESTIGATIONS

Surveyor Television Investigations
(Contract WO-3027, terminated June 30, 1968)

The successful soft landing of Surveyor VII January 10, 1968 on the rim of the crater Tycho in the southern highlands of the Moon brought to conclusion the highly successful Surveyor project. Five Surveyor spacecraft soft-landed on the Moon between June 1966 and January 1968 and returned over 87,000 pictures from the lunar surface. The following is a summary of the preliminary results obtained from an analysis of these pictures by members of the Surveyor Television Investigator Team of the U.S. Geological Survey.

At each of the Surveyor landing sites, the surface is covered by a layer of fragmental debris, which is littered with a variety of rock fragments. Some fragments lie on the surface, and others are partly embedded to various depths in a finer grained material. The fragments are scattered somewhat irregularly, and in most places sparsely, but strewn fields of blocks are found around some of the larger craters. The Surveyor VII landing site has the largest number and variety of rock fragments, whereas the Surveyor V and VI sites have the fewest resolvable rock fragments. Most of the resolvable fragments on the surface are significantly brighter, under all observed angles of illumination, than the unresolved fine-grained matrix. Most of the fragments appear to be dense, coherent rock, while some appear less dense and porous. Most fragments are relatively angular, but some well-rounded fragments are also present and most of these appear to be fairly deeply embedded in the lunar surface material. On the whole, most fragments tend to be equant in shape, but some are distinctly tabular and a few have the form of sharp, narrow wedges, some of which protrude from the surface like a spike.

Many blocks at the Surveyor VII site, and a few at the Surveyor I site, are distinctly vesicular. Spotted rocks, first observed at the Surveyor I site and also seen at the Surveyor V site, are common near Surveyor VII. Light spots on these rocks generally have indistinct boundaries and vary in size from a few millimeters to several centimeters across. The lighter material commonly forms slight bumps, or protrusions, on the surface of the fragment, suggesting that this material is more resistant to lunar erosional processes.

A knobby, pitted surface is the most common surface texture developed on the bright, coarse, rounded rock fragments. The pitted texture probably is produced by the same process that rounds off the edges of the fragmental material--impact of small particles. Further evidence that the surfaces of the rocky fragments have been eroded by abrasion was found on one of the rocks overturned by the Surveyor VII surface sampler. This rock was rounded on the exposed side and angular underneath.

Some coarse fragments on the lunar surface are clearly aggregates of smaller particles. Some aggregates are compact and angular, whereas others appear to be porous and probably are only weakly compacted.

Between 4 and 18 percent of the lunar surface is covered by fragments large enough to be resolved by Surveyor television cameras (larger than 1 mm). The size-frequency distribution of resolvable fragmental debris at each Surveyor landing site can be represented by a simple power function. At the mare sites, the exponent of the size-distribution function is uniformly less than -2; whereas at the Surveyor VII site, on the rim flank of Tycho, the exponent is -1.8. Fragments coarser than 10 cm are 5 to 10 times more abundant on the rim of Tycho than on the maria.

Small craters account for the irregularities of largest relief on the surfaces at the mare landing sites. Most of the small craters at each of the landing sites have a cup shape with walls and floors concave upward; most have low, subdued rims, but some are nearly rimless. Crater chains and dimple-shaped craters lacking raised rims are common at the Surveyor V site and were observed at the Surveyor III site. They are inferred to have been formed by drainage of the surficial fragmental debris into subsurface fissures. Most of the cup-shaped craters are probably of impact origin.

Many irregular craters, ranging in size from a few centimeters to several meters in diameter and lined with clods of fine-grained material, were observed at all landing sites. These are inferred to be secondary impact craters formed by cohesive blocks or clods of weakly cohesive, fine-grained material ejected from nearby primary craters.

The cumulative size distribution of small craters a few centimeters to several tens of meters in diameter is consistent with a power law having an exponent of -2. This corresponds to that expected for a steady-state population of craters produced by prolonged, repetitive bombardment by meteoroids and by secondary fragments from the Moon. There are fewer craters larger than 8 m in diameter at the Surveyor VII site than at the mare landing sites, which indicates that the Tycho rim material on which Surveyor VII landed is relatively young.

Where the fine-grained matrix of the surface material was compressed and smoothed by the Surveyor footpads or the surface sampler, the photometric properties were changed. The photometric function of the smoothed surfaces is more like that of a Lambertian scatterer than the undisturbed, fine-grained lunar material. This indicates that the pore spaces of the fine-grained material tend to be filled in by compression against smooth surfaces on parts of the spacecraft.

The average thickness of the lunar regolith, or debris layer, was determined for each of the mare landing sites from the depth of the smallest craters with blocky rims. The thickest regolith (10 to 20 m) was found at the Surveyor VI site. Near Surveyor I the regolith is 1 to 2 m thick, and at the Surveyor V site it is leas than 5 m thick. Surveyor III landed inside a subdued 200-m-diameter crater. The thickness of the regolith ranges from about 1 to 2 m on the rim of this crater to perhaps 10 m or more at the crater center.

Television observations with color filters indicate that the lunar surface is gray, even in disturbed areas. Color differences were not observed among any of the coarse blocks so far examined, which are all gray but lighter than the fine-grained gray matrix of the surface. Photometric measurements made at each Surveyor landing site on the lunar mare show that the normal luminance factor (normal albedo) ranges from 7.3 to 8.2 percent on undisturbed surfaces and from 5.5 to 6.1 percent on surfaces disturbed by the footpads and by the surface sampler. The normal luminance factor for the fine-grained, undisturbed and disturbed material at the Surveyor VII site is higher than that of the fine-grained surface material on the maria. The luminance factor for the rock fragments ranges from 14 to 22 percent both on the maria and on the rim flank of Tycho. Light scattered from the surfaces of some rock fragments at the Surveyor VII site is as much as 30 percent polarized at phase angles near 120°. This suggests that these rocks are crystalline or glassy, and that their surfaces are relatively free of fine particles.

Observations of the fine-grained parts of the lunar surface disturbed by the landing and liftoff of the Surveyor VI spacecraft, and by rolling fragments set in motion by the spacecraft, have shown that lunar material exposed at depths no greater than a few millimeters has a significantly lower normal luminance factor than the undisturbed surface. A similar, abrupt decrease in normal luminance factor at depths of 3 mm or less was observed at the Surveyor III and V landing sites. The occurrence of this rather sharp contact of material with contrasting optical properties at widely separated localities on the Moon suggests that some process, or combination of processes, brightens the material at the lunar surface. If this is true, a complementary process of darkening may occur at depths of a few millimeters or more, so that the abrupt albedo contact is not destroyed as a result of repetitive turnover of the lunar surface by solid-particle bombardment.

Topographic and planimetric maps at several scales have been made of each of the landing sites from the Surveyor pictures.

Photography from Manned Moon-orbiting Spacecraft
(Contract T-66353G)

Harold Masursky and D. E. Wilhelms, along with James H. Sasser of the Manned Spacecraft Center, Douglas D. Lloyd of Bellcomm, and Hellmut H. Schmid of the U.S. Coast and Geodetic Survey, prepared a proposal for a photographic experiment on manned missions orbiting the Moon in a Command and Service Module during Apollo missions. Preliminary selection of sites for the Apollo 8 mission was begun during the contract year.

Mars
(Contract W-12,650, FY 68 only)

A proposal for an investigation of the regional geology of Mars as part of the television experiment on the 1971 Mariner mission was prepared and submitted in June 1968. A team of seven coinvestigators with Harold Masursky as principal investigator was appointed by NASA in October. M. H. Carr, J. F. McCauley, D. E. Wilhelms, D. J. Milton, R. L. Wildey, W. T. Borgeson, and R. M. Batson are the coinvestigators. Formal participation in the Mariner program began with assignment of investigators to seven discipline-oriented teams collectively responsible for conduct of the television experiment.

A study of the Mariner IV Mars data was conducted by J. F. McCauley. It includes a comparison between certain types of Mars features and inferred lunar analogs which may aid in the interpretation of future low-resolution pictures of Mars. A report is currently being prepared and will be submitted for publication in the spring of 1969.

Proposals, solicited by NASA for participants on the team for the development of scientific instruments to be carried on the Mars 1973 lander mission were provided by Harold Masursky, E. C. Morris, H. E. Holt, H. J. Moore, R. M. Batson, and J. D. Alderman.

Jupiter
(Contract W-12,650)

A proposal, solicited by NASA, for a spin-scan imaging experiment on the Pioneer/Jupiter mission in 1972 was submitted by R. L. Wildey, D. N. Tompkins, H. J. Moore, and S. S. C. Wu. Large dynamic response is in various spectral zones and, with polarizers, allows for eight frames of all sides of the Jovian disk. The instrument acts as its own horizon sensor but also may be coupled to other instruments for this purpose.